Heavy-ion induced molecular desorption: a review of three years of measurements at LINAC 3

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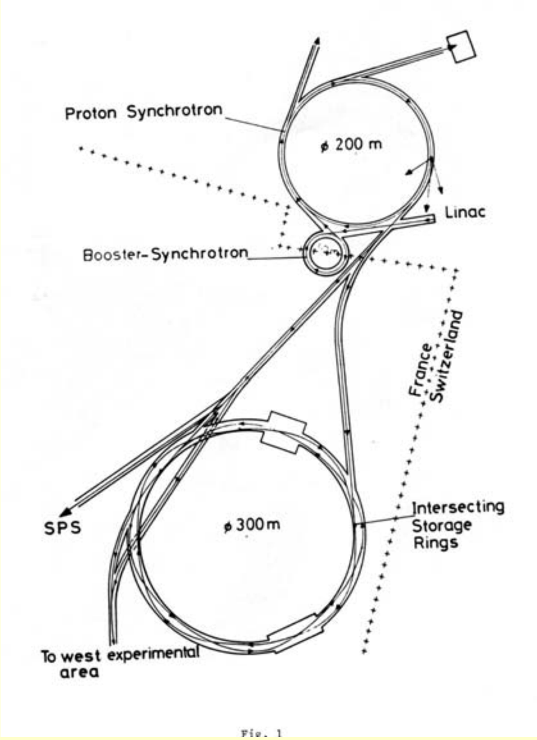
Outline

- Dynamic pressure rises at ISR and LEAR
- LEIR vacuum requirements
- Review of LINAC 3 desorption studies
- Desorption experiment at the SPS

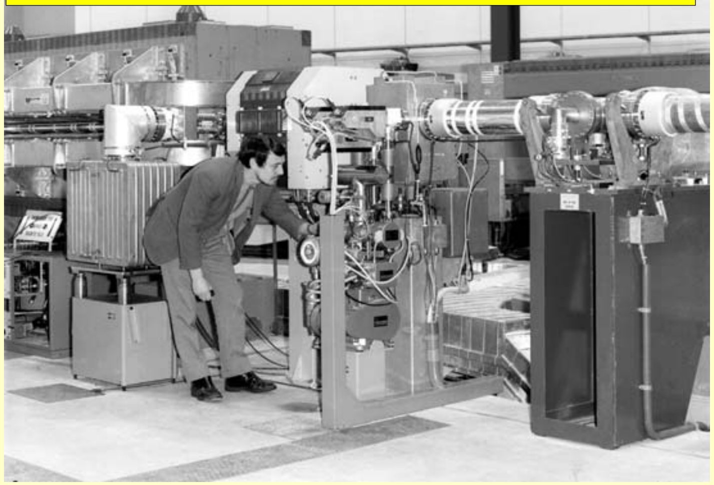
13th ICFA Beam Dynamics Mini-Workshop
Beam Induced Pressure Rise in Rings
Brookhaven National Laboratory, December 9 - 12, 2003

CERN Intersecting Storage Rings (ISR)



pp collisions (26 GeV)

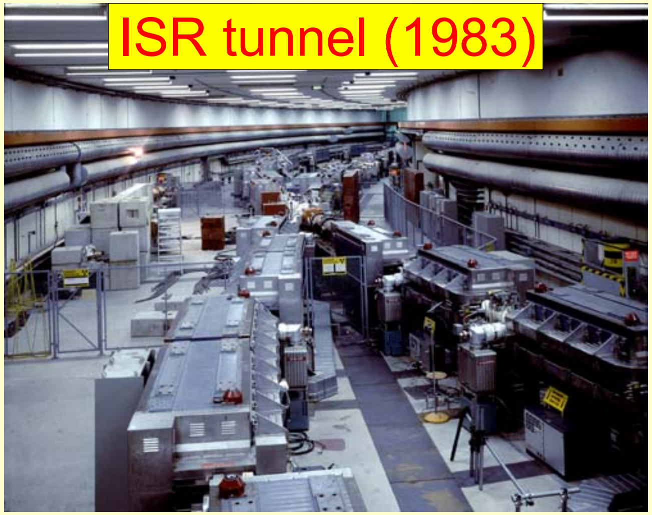
ISR vacuum system (1971)



Length: ~2 × 1 km (double ring)
Average pressure: 10^{-9} Torr
Material: stainless steel
Bakeout: 300°C

ISR design study (May 1964)

ISR tunnel (1983)

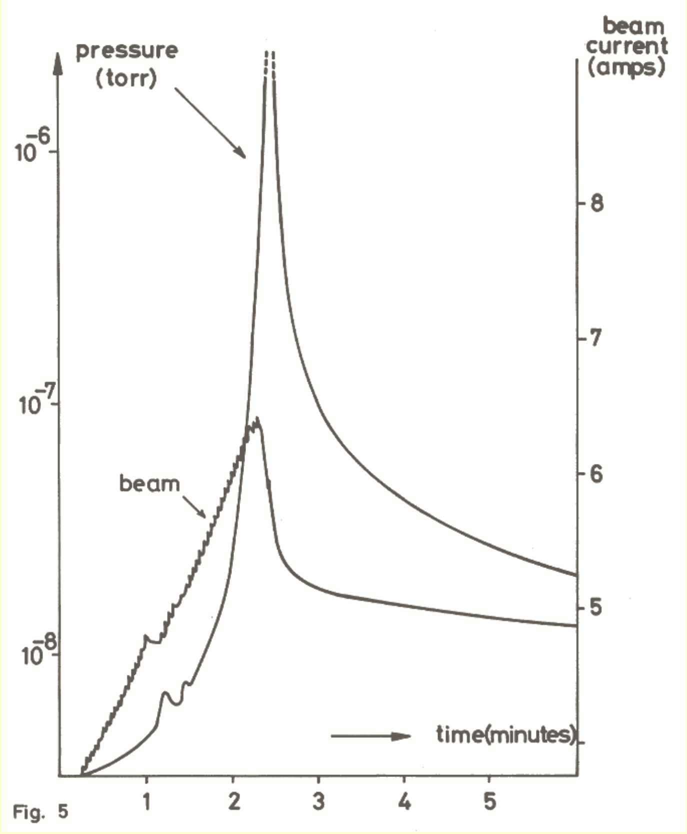


ISR tunnel (2001)

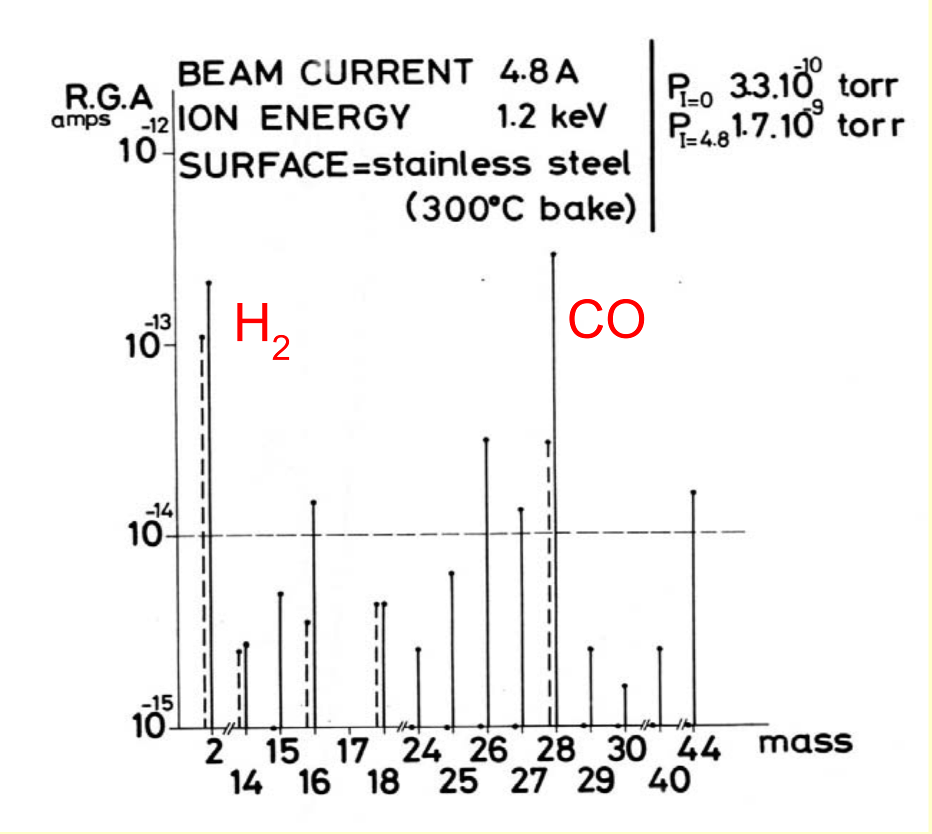
ISR pressure rise

First observation of "ion-induced" vacuum instability

The ISR pressure bump



Gas composition of a ISR pressure bump

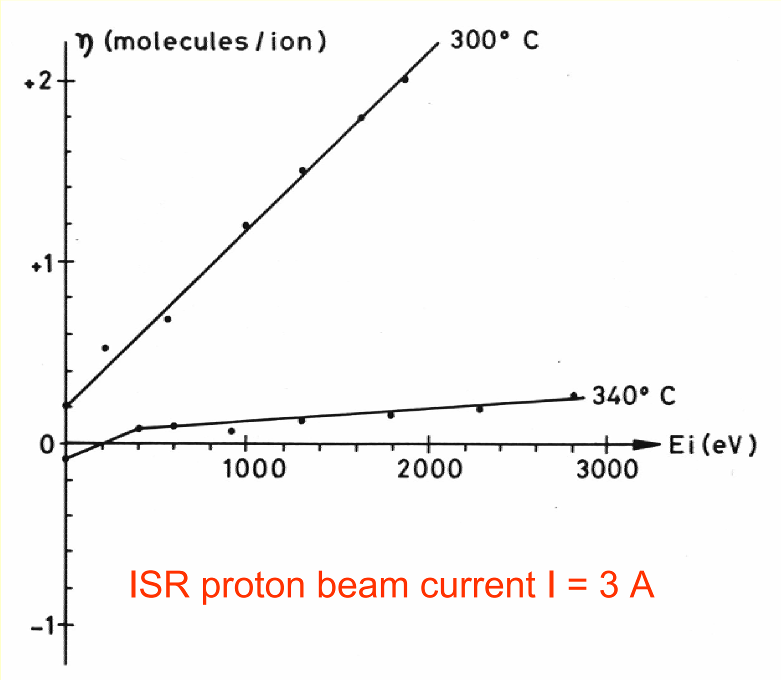


O. Gröbner and R.S. Calder (1973)

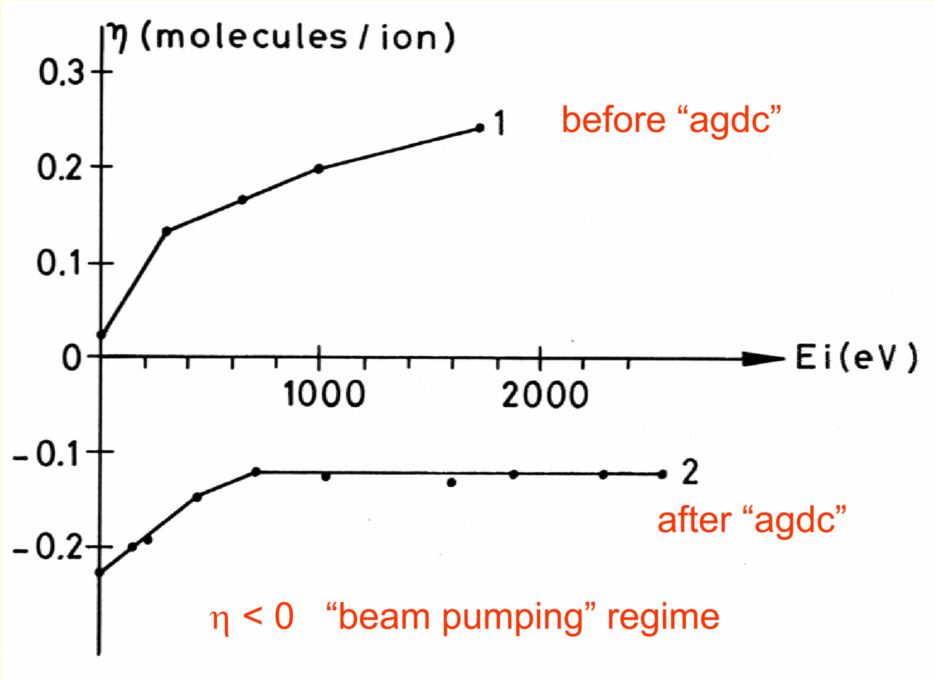
Cure of the ISR pressure rise

Desorption yield depends on surface treatments

Dependence on bakeout temperature



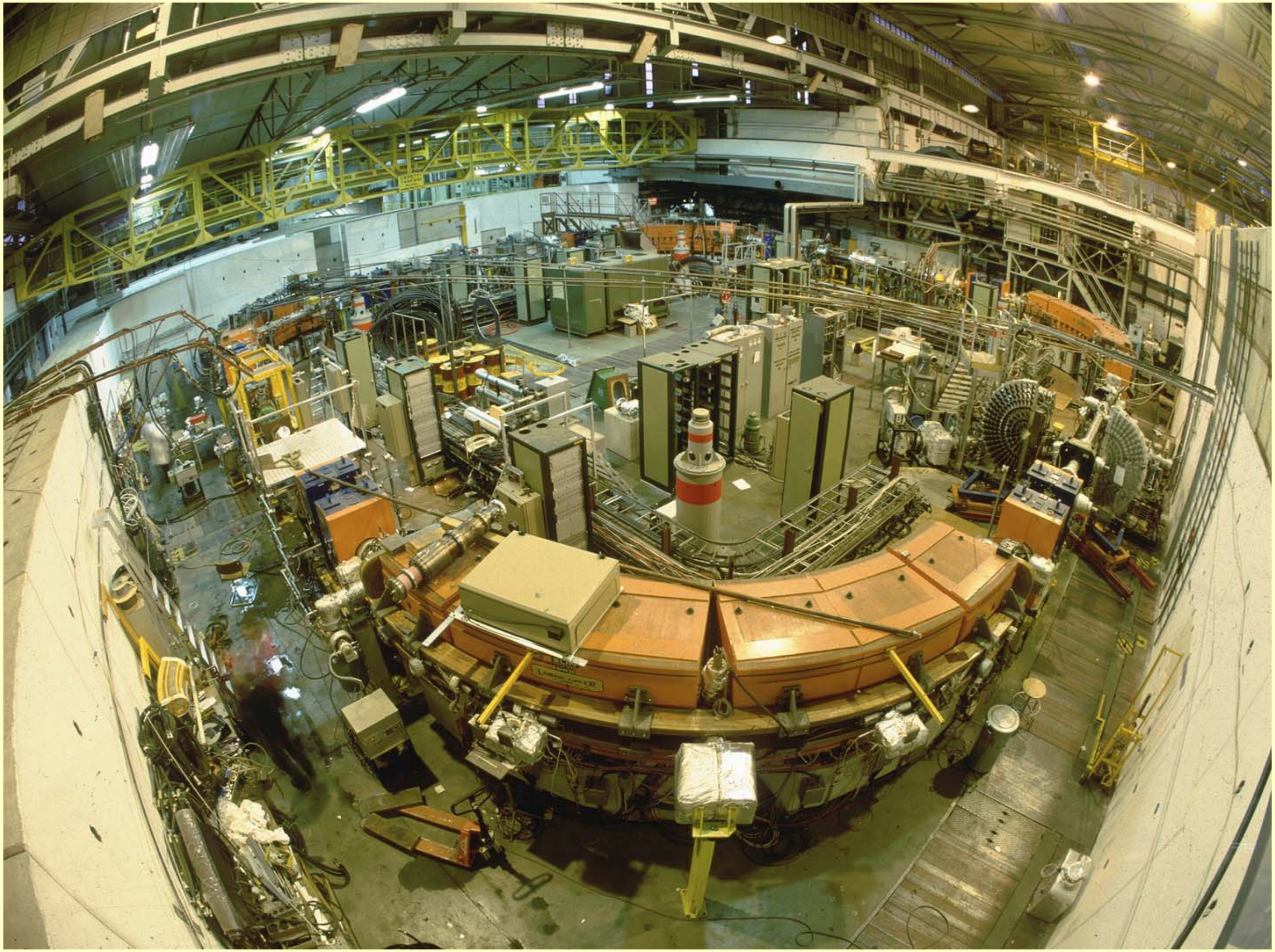
Argon glow discharge cleaning (agdc) + *in-situ* bakeout at 300˚C



Cure for the ISR: Improvement of the pumping system + reduction of desorption yield due to improved bakeouts and/or glow discharge cleaning

O. Gröbner and R.S. Calder (1973)

LEAR ring 1997



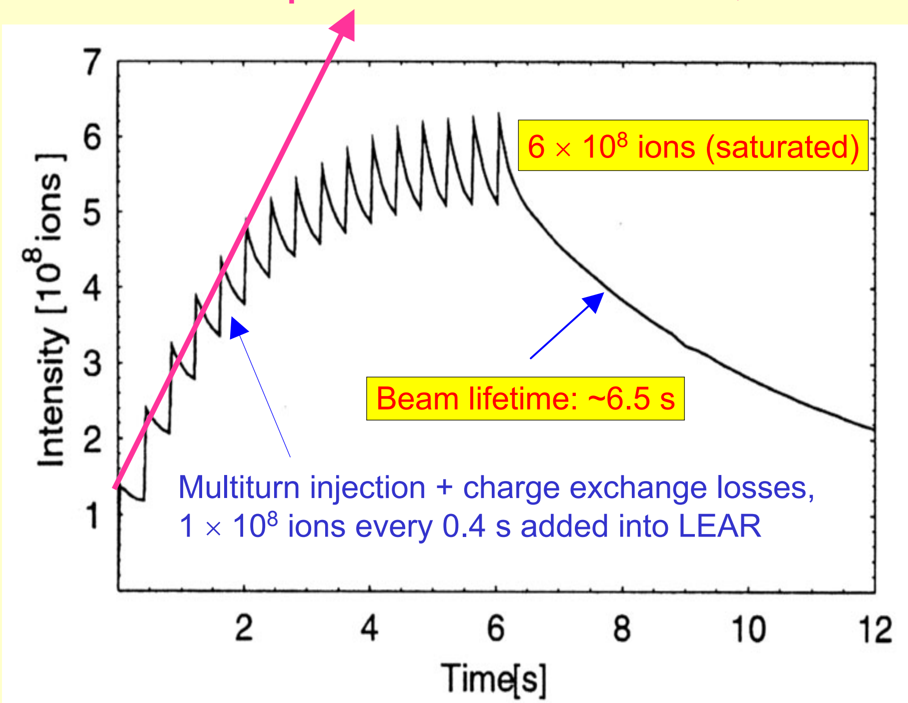
Ion-induced pressure rise during Pb^{54+} (4.2 MeV/u) accumulation in LEAR

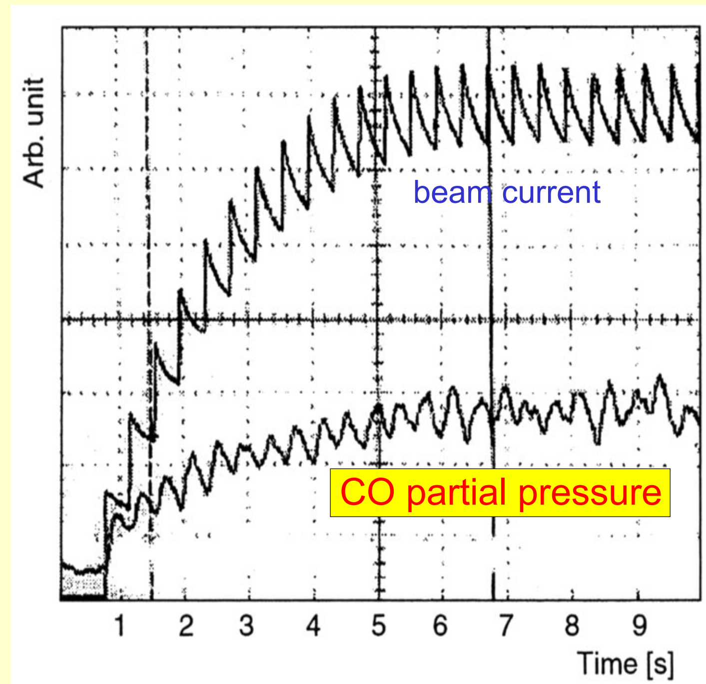
– LEAR <u>static</u> vacuum: 5×10^{-12} Torr

– Dynamic pressure rise up to 3×10^{-11} Torr, not understood

– Outgassing of vacuum equipment due to the <u>impact of lost lead ions ?!</u>

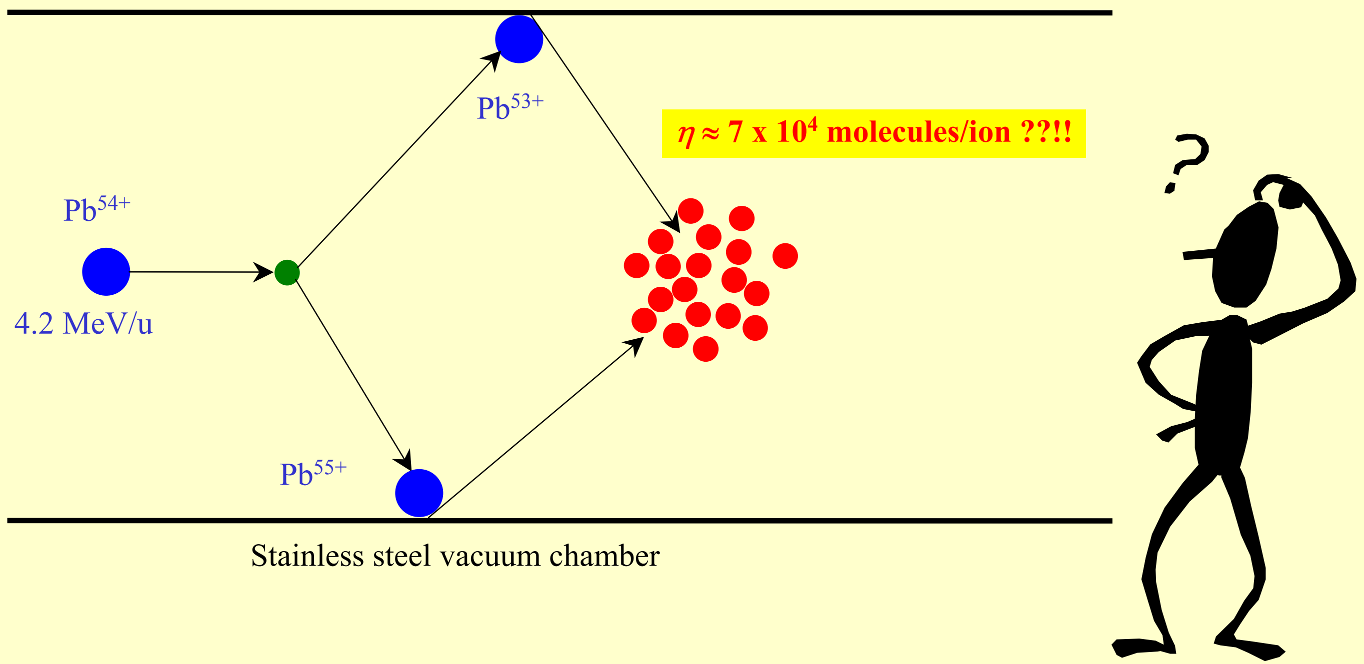
LHC requests: 9×10^{8} ions, τ = 30 s



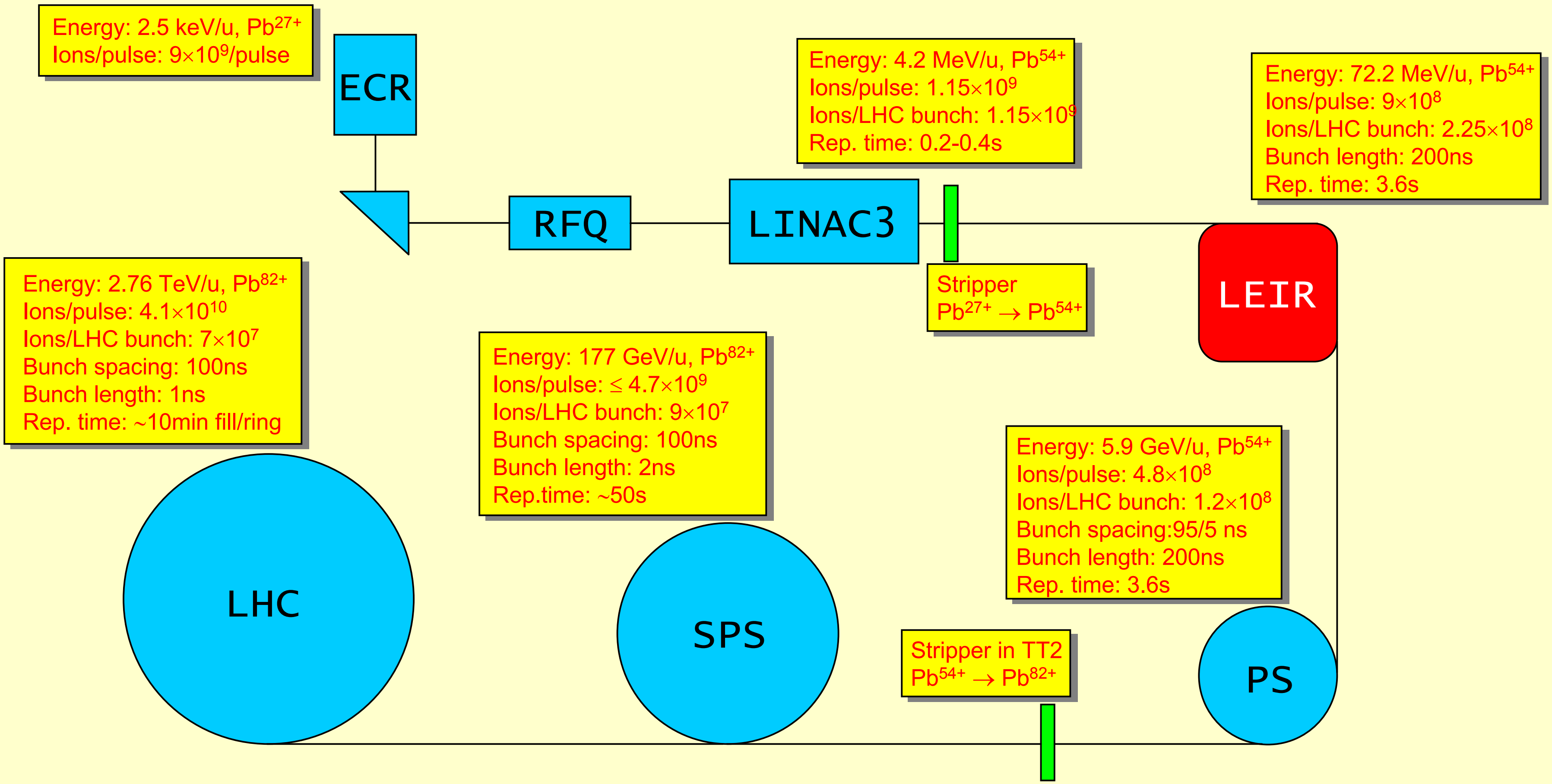


J. Bosser *et al.* (1999)

Mechanism of beam-loss induced pressure rise in LEAR



LHC requirements for heavy ions
The Pb Injector Chain



LEIR vacuum requirements

Basics: lifetime & gas density

- Beam lifetime

$$\frac{1}{\tau} = \beta \times c \times \sigma_{tot} \times n$$

– c: speed of light, n: gas density (independent of the gas species)

- Gas density

– $n \approx 9.656 \times 10^{24} \times p/T$ molec./m^3

p: pressure (Torr), T: temperature (Kelvin)

one finds at 20°C, 1 Torr: $n \approx 3.29 \times 10^{22}$ molec./m^3

- Gas "mixture"

– replace $\sigma_{tot} \times n$ by $\Sigma \sigma_i \times n_i$

$$\frac{1}{\tau_{total}} = \frac{1}{\tau_{H_2}} + \frac{1}{\tau_{CH_4}} + \frac{1}{\tau_{CO}} + \frac{1}{\tau_{CO_2}} + \ldots$$

Cross sections needed
to calculate the gas density

Dynamic pressure

- Required dynamic gas densities n & partial pressures P
  - Charge-exchange of a heavy ions, capture & loss of electrons
  - the capture process dominates in LEIR

Gas	*Franzke* τ = 30 s n [m^{-3}]	*Schlachter* τ = 30 s n [m^{-3}]	*Franzke* τ = 30 s P [Torr] @ 20°C	*Schlachter* τ = 30 s P [Torr] @ 20°C
H_2	$7.22 \times 10^{+11}$	$2.71 \times 10^{+13}$	**2.20×10^{-11}**	**8.24×10^{-10}**
He	$7.23 \times 10^{+11}$	$2.98 \times 10^{+12}$	2.20×10^{-11}	9.05×10^{-11}
CH_4	$1.46 \times 10^{+11}$	$2.30 \times 10^{+11}$	**4.45×10^{-12}**	**6.99×10^{-12}**
H_2O	$1.49 \times 10^{+11}$	$1.70 \times 10^{+11}$	4.54×10^{-12}	5.17×10^{-12}
N_2	$1.06 \times 10^{+11}$	$9.88 \times 10^{+10}$	3.23×10^{-12}	3.01×10^{-12}
CO	$1.07 \times 10^{+11}$	$9.88 \times 10^{+10}$	**3.24×10^{-12}**	**3.00×10^{-12}**
Ar	$9.50 \times 10^{+10}$	$8.33 \times 10^{+10}$	2.89×10^{-12}	2.53×10^{-12}
CO_2	$6.81 \times 10^{+10}$	$6.26 \times 10^{+10}$	**2.07×10^{-12}**	**1.90×10^{-12}**

4.2 MeV/u
Pb^{54+}

Total cross sections calculated with Franzke's and Schlachter's formulae

↓

Gas density n for τ = 30 s

↓

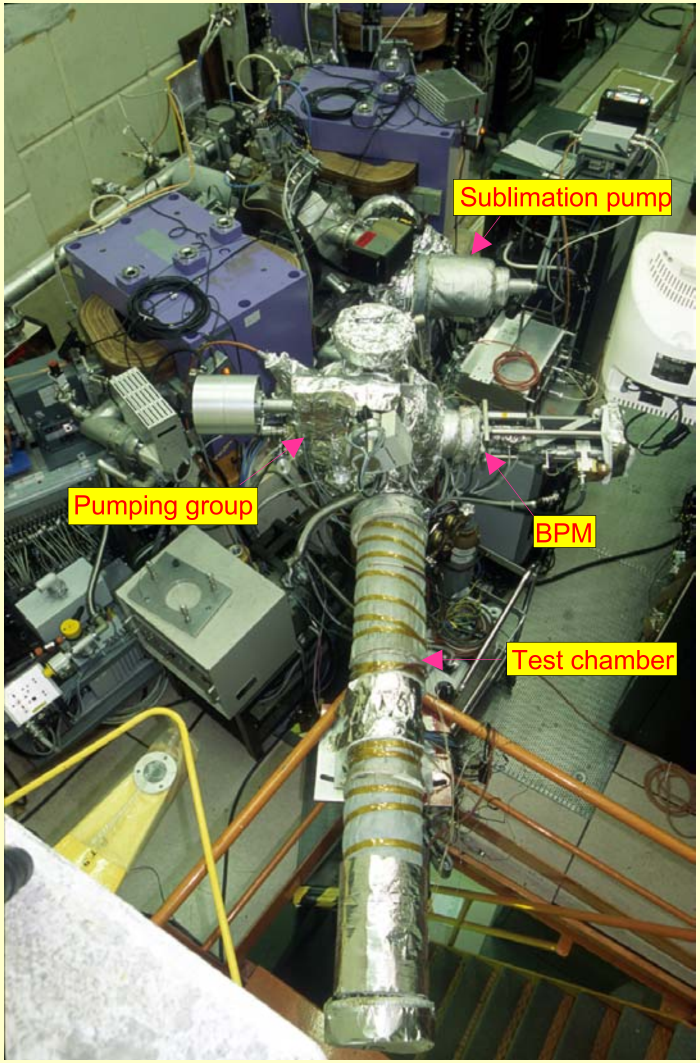
Gas composition

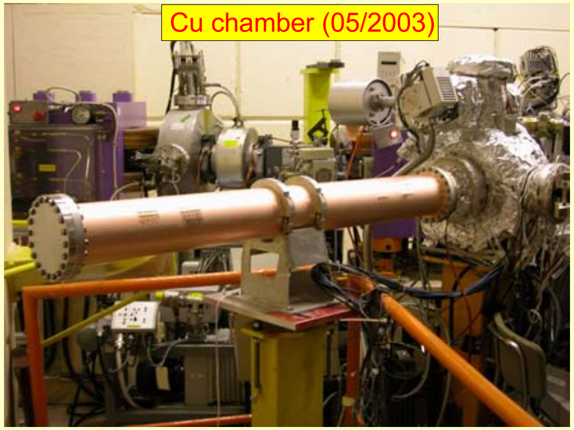
↓

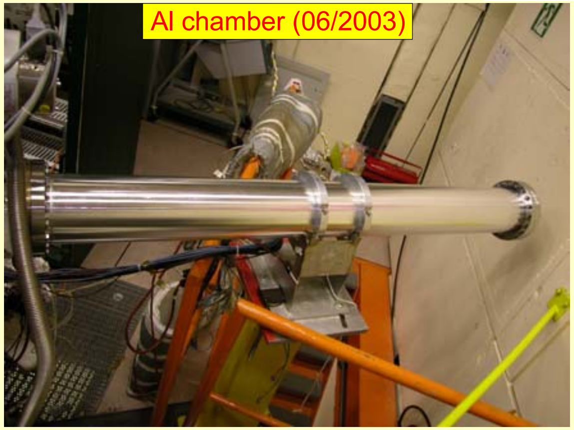
$P_{dynamic}$ for LEIR

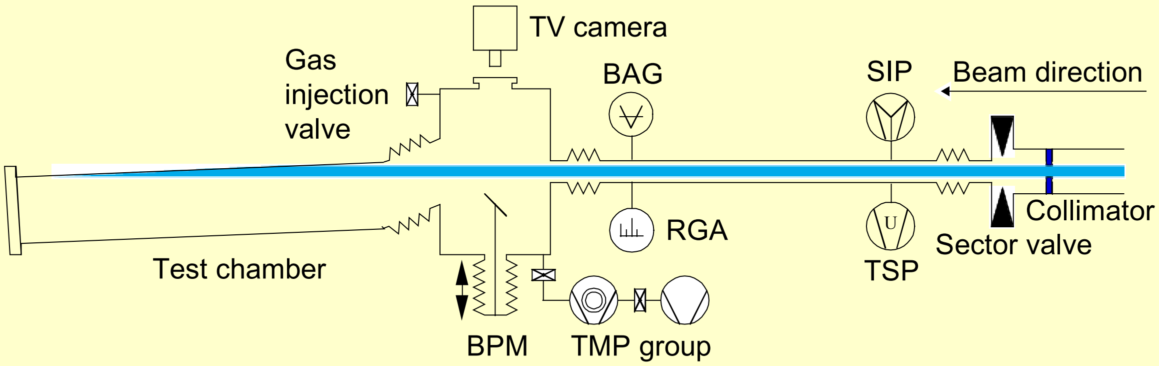
- Typical gas composition under heavy ion bombardment
  - Results from LINAC 3 desorption experiment:
    CO (72%), CO_2 (18%), CH_4 (7%), H_2 (3%).
- Required average dynamic pressure in LEIR
  - **$P_{dynamic} \approx 3 \times 10^{-12}$ Torr !**

Experimental setup at LINAC 3









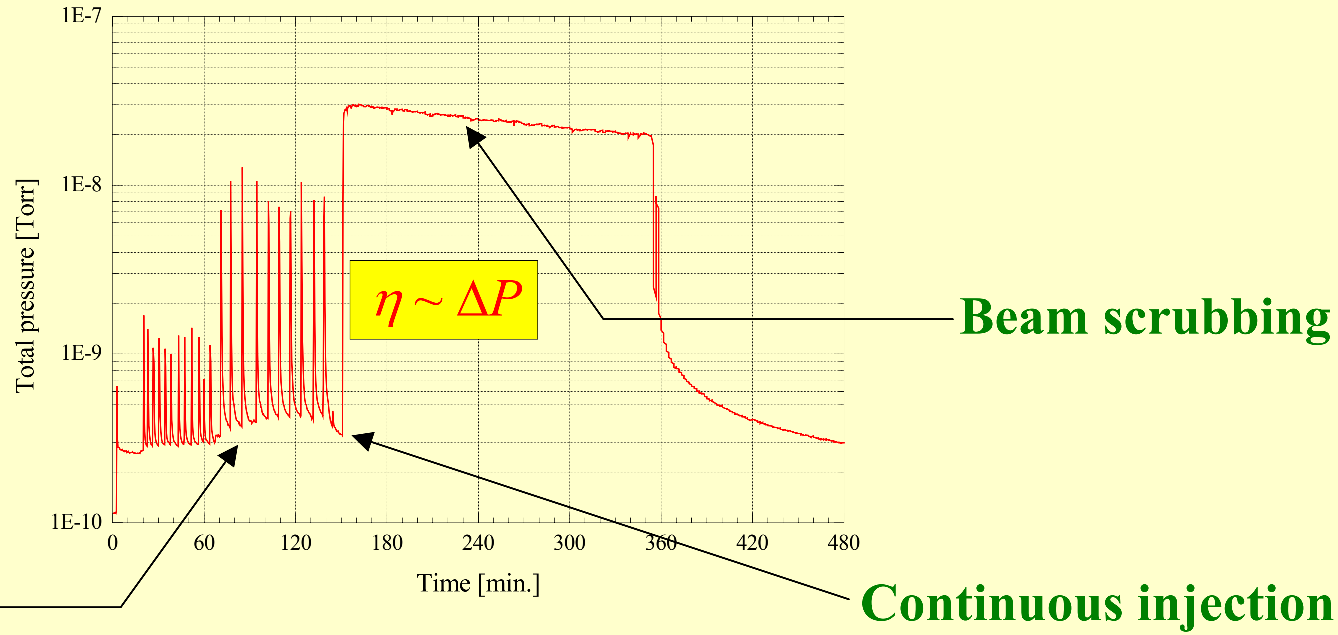
Particles: ~10^{10} Pb^{27+} or ~ 1.5 × 10^{9} Pb^{53+}

Repetition time: 1.2s

Impact angles studied: θ = 89.2°, 84.8°, 0° (perpend.)

Desorption yield measurements

η : desorbed molecules/impacting ion



$$\eta_{eff,ss} = \frac{\Delta P \times V}{N_{Pb} \times k_B \times T} = G \times \frac{\Delta P \times V}{N_{Pb}}$$

$$\eta_{eff} = \frac{\Delta P \times S}{\dot{N}_{Pb} \times k_B \times T} = G \times \frac{\Delta P \times S}{\dot{N}_{Pb}}$$

ΔP: partial pressure increase, V: volume, S: pumping speed

N_{Pb}: number of impacting ions, $\dot{N}_{\mathrm{Pb}}$: flux of impacting ions

k_{B}: Boltzmann constant, T: temperature

G: $\approx 3.2 \times 10^{19}$ at 300 K, converts (Torr $\times\ \ell$) into molecules

Review of LINAC 3 experiments 2001-2003

15 vacuum chambers built, 21 different surfaces tested

Results presented for: 4.2 MeV/u, Pb^{53+}, $\Theta = 89.2°$

Glow discharges, polishing

- As received
- Glow discharged: Ar-O_2, He-O_2
- Chemical polishing: 50µm
- Electropolishing: 50 µm, 150µm

Noble metal coatings

- Galvanic coating: Au/Ni/ss (30 µm, 2 µm, ss)
- Galvanic coating: Ag/Ni/ss (2 µm, 2 µm, ss)
- Sputtering: Pd/ss (0.6 µm, ss)

Getter materials

- Sputtered NEG: TiZrV/ss (2 µm, ss)
- Getter strips St707: ZrVFe (70 µm)

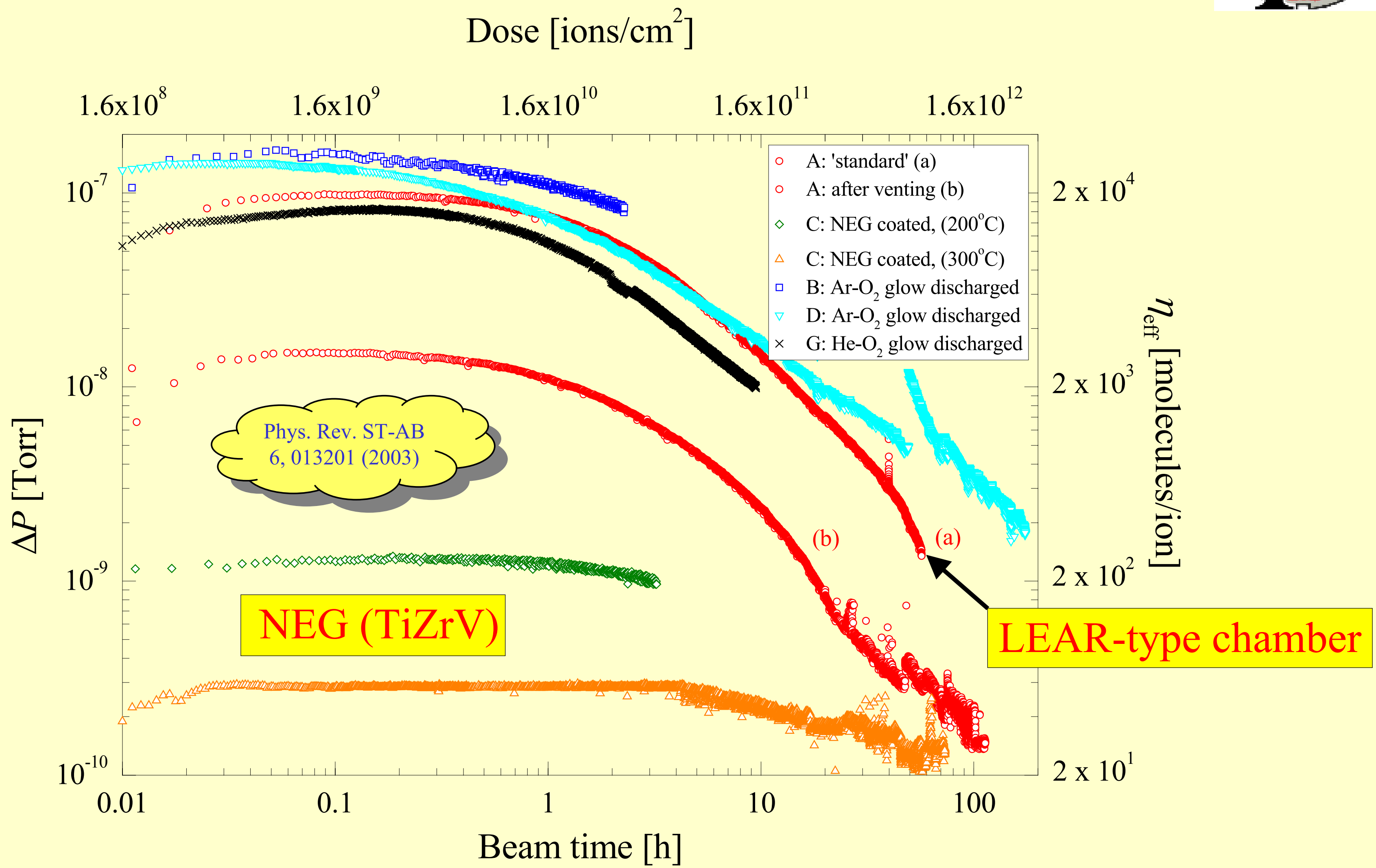
Vacuum firing

- Vacuum firing 1050°C ÷ 950 °C
- 304L (<u>not</u> vac. fired) ÷ 316 LN
- 316 LN "getter purified"
- Bakeout temperature 300°C ÷ 400 °C
- Venting after beam scrubbing

Other materials Cu, Al, Si, Mo

LINAC 3 beam scrubbing review (1/8)

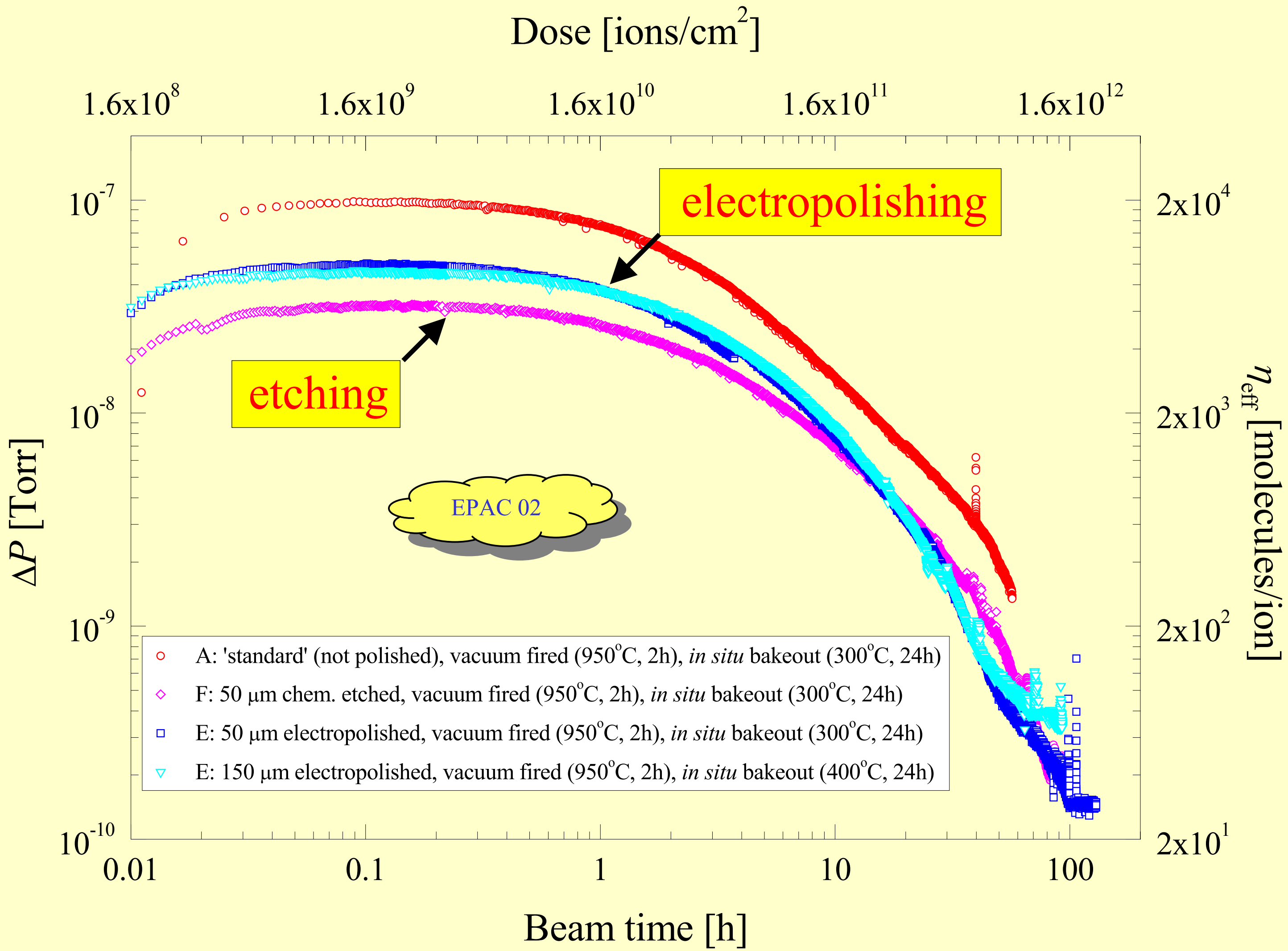
'Standard' 316 LN ÷ Ar-O_2 & He-O_2 glow discharges ÷ sputter-coated NEG



E. Mahner, J. Hansen, J.-M. Laurent, N. Madsen

LINAC 3 beam scrubbing review (2/8)

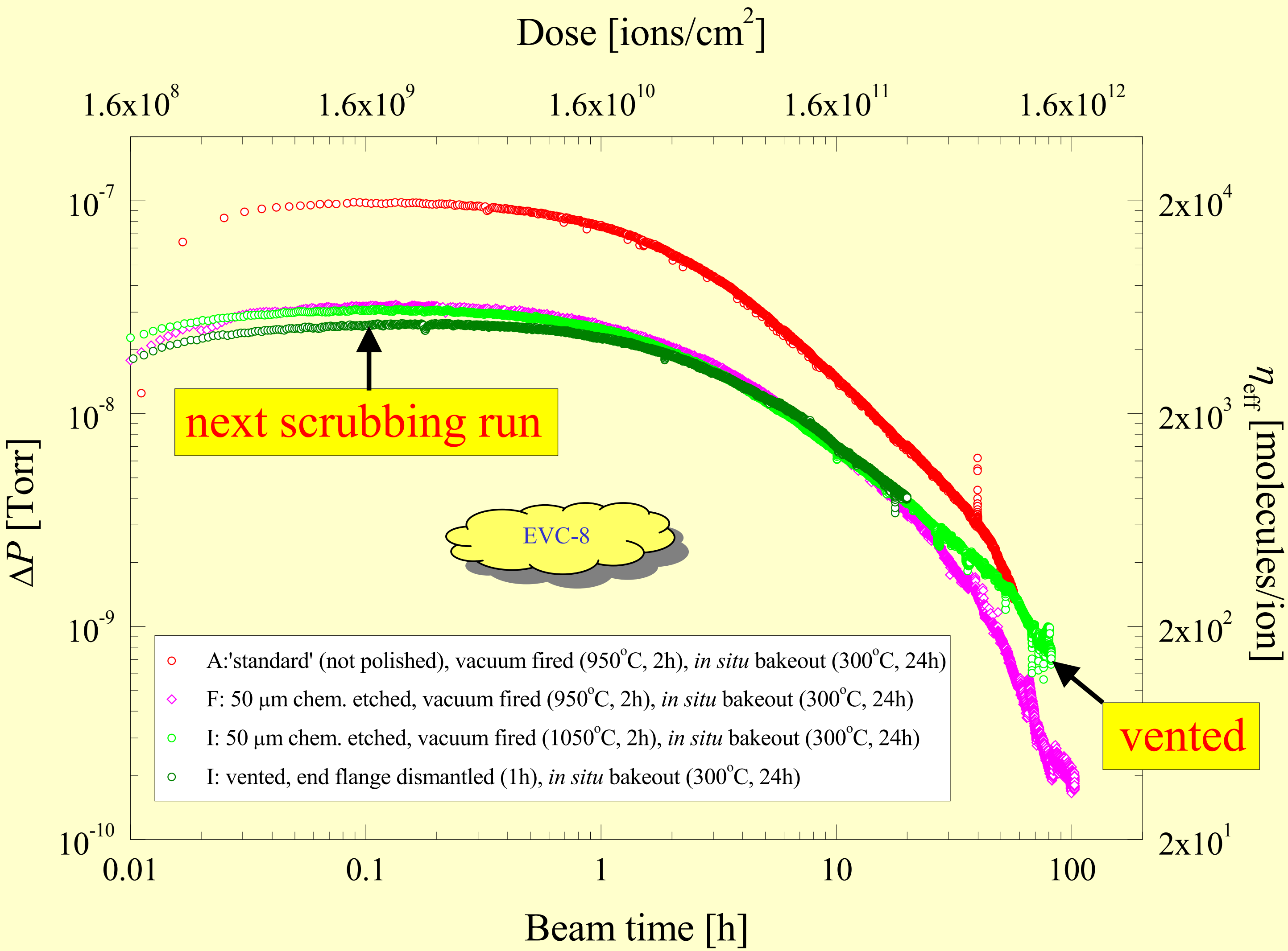
'Standard' 316 LN ÷ chemical etching ÷ electropolishing



E. Mahner, J. Hansen, D. Küchler, M. Malabaila, M. Taborelli

LINAC 3 beam scrubbing review (3/8)

Effect of venting after 82h scrubbing

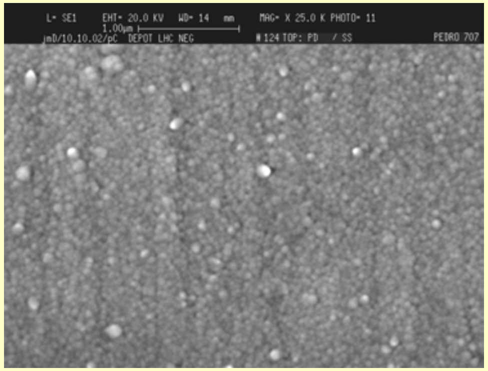


E. Mahner, J. Hansen, D. Küchler, M. Malabaila, M. Taborelli

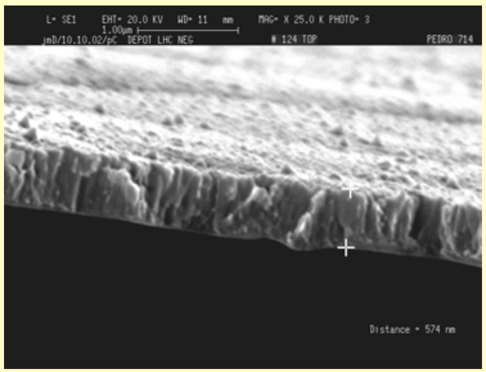
LINAC 3 beam scrubbing review (4/8)

Au ÷ Ag ÷ Pd films ÷ St707 getter strips ÷ sputter coated NEG

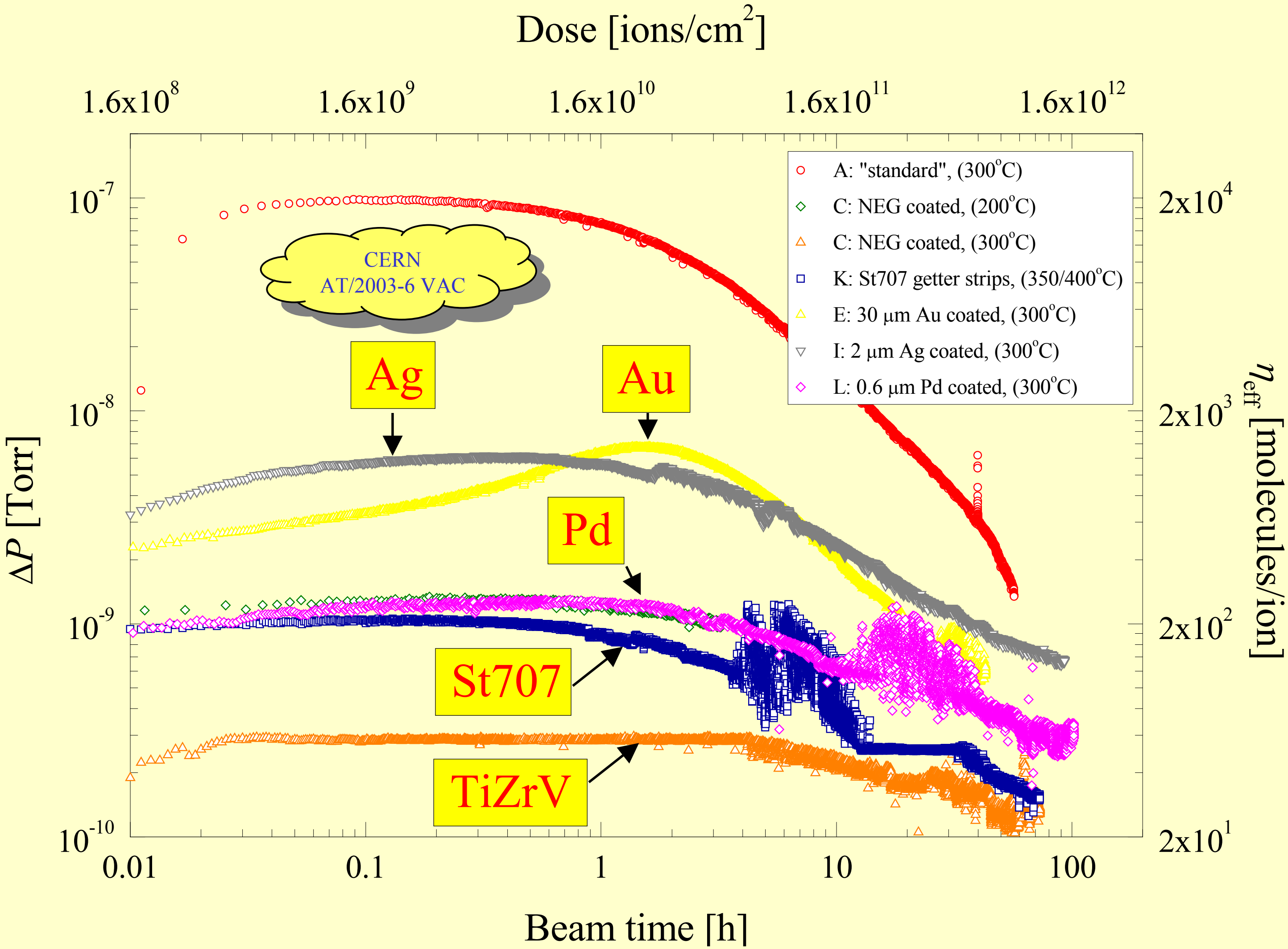
sputtered Pd



Surface morphology



Thickness: e = 0.6 μm

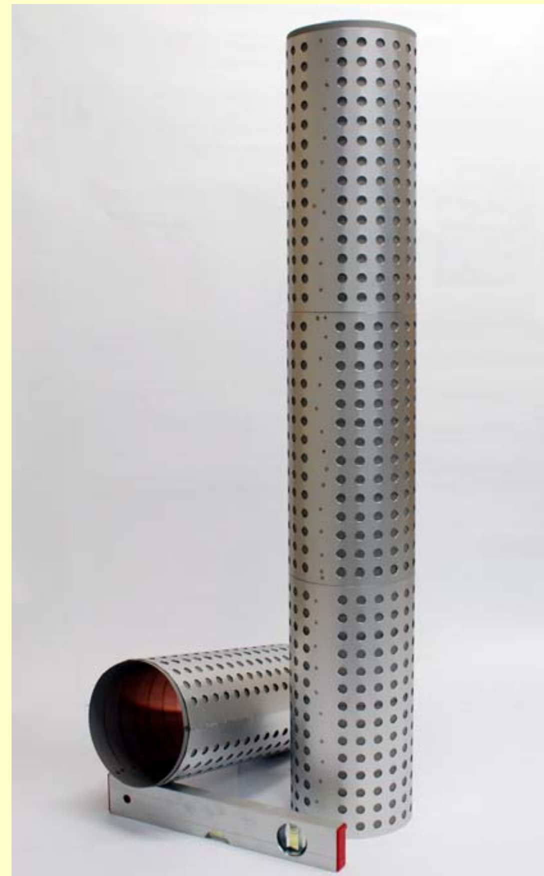


LINAC 3 beam scrubbing review (5/8)

"Total NEG pump" tested at LINAC 3

St707 strips: ≈25 m total length, 30 mm width

Strips spot welded on 950°C vacuum fired stainless steel cylinders
in situ activation during bakeout: 350°C (24h) + 400°C (3h)



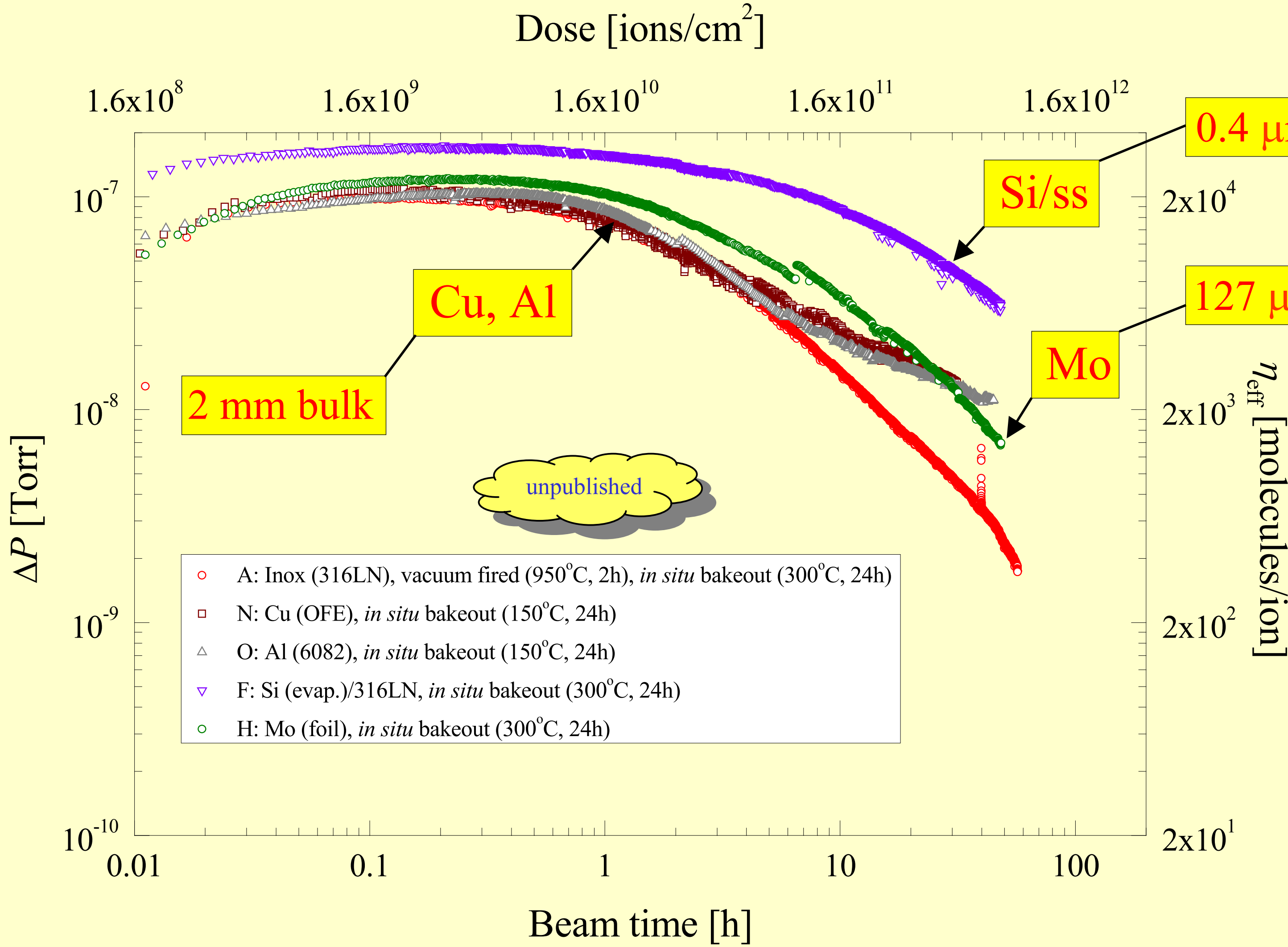
Very large pumping speeds(*):

S_{H_2}: 1000 $l.s^{-1}.m^{-1}$ S_{CO}: 2000 $l.s^{-1}.m^{-1}$
S_{CO_2}: 1500 $l.s^{-1}.m^{-1}$ S_{N_2}: 450 $l.s^{-1}.m^{-1}$

(*)C. Benvenuti, P. Chiggiato, J. Vac. Sci. Technol. **A14**, 3278 (1996)

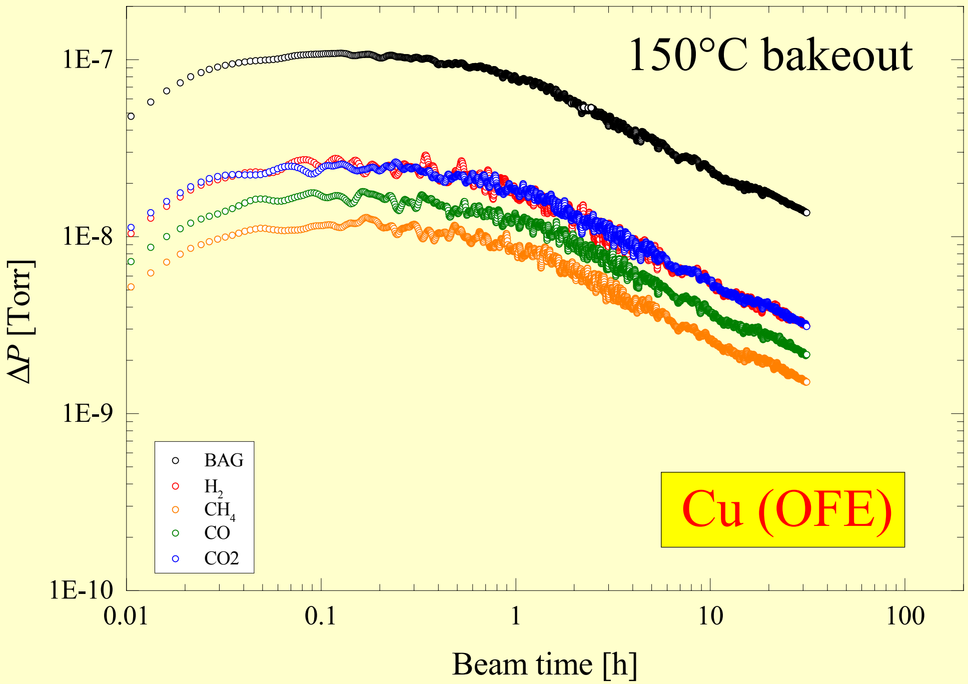
LINAC 3 beam scrubbing review (6/8)

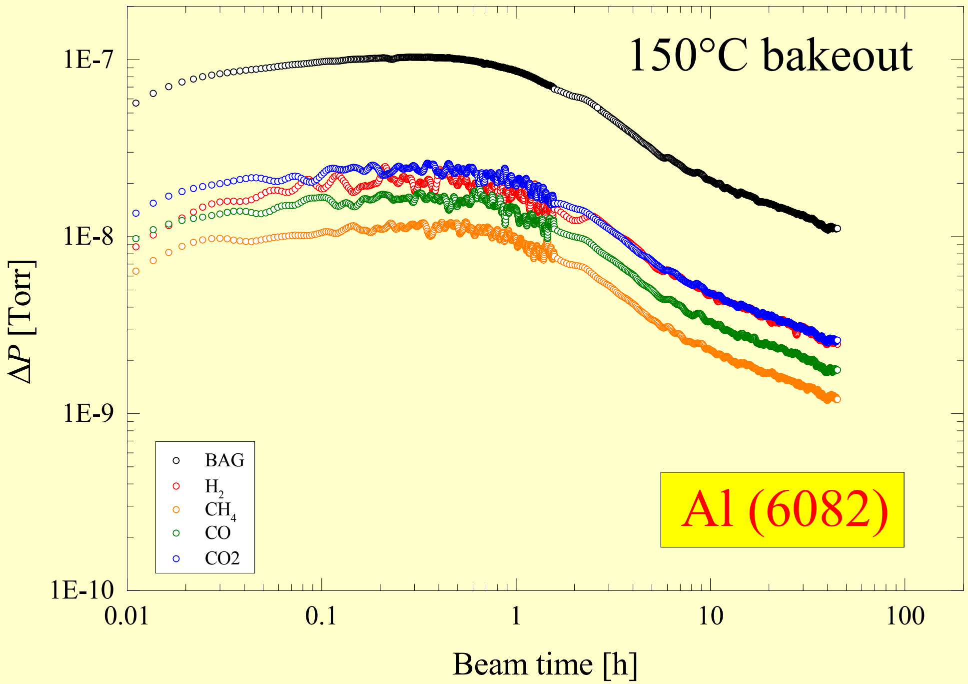
Other materials: Cu, Al, Si/ss, Mo

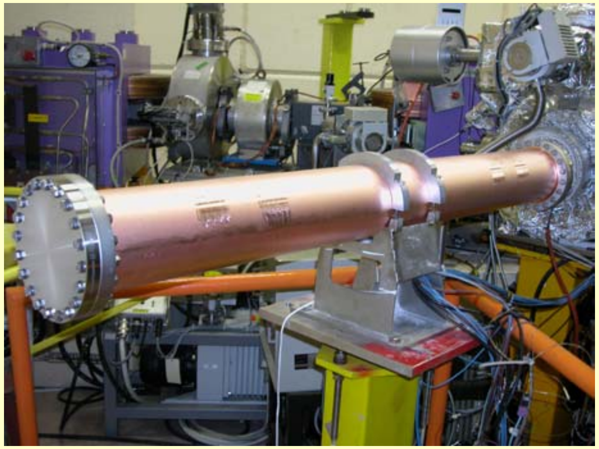


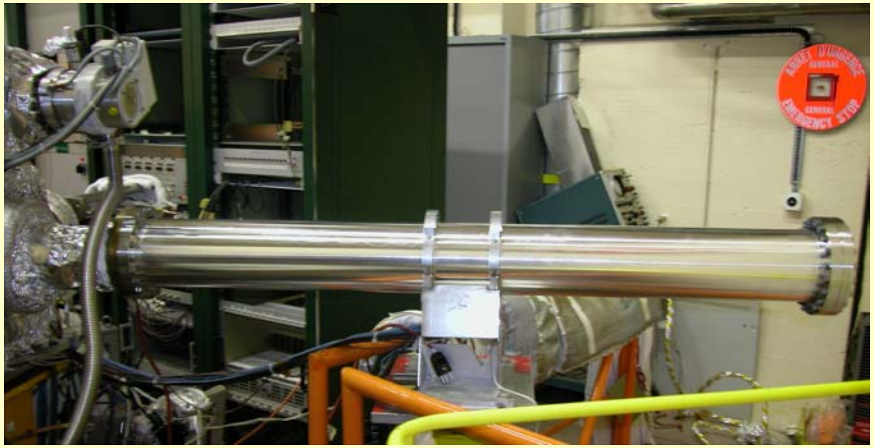
LINAC 3 beam scrubbing review (7/8)

Cu & Al: partial pressures



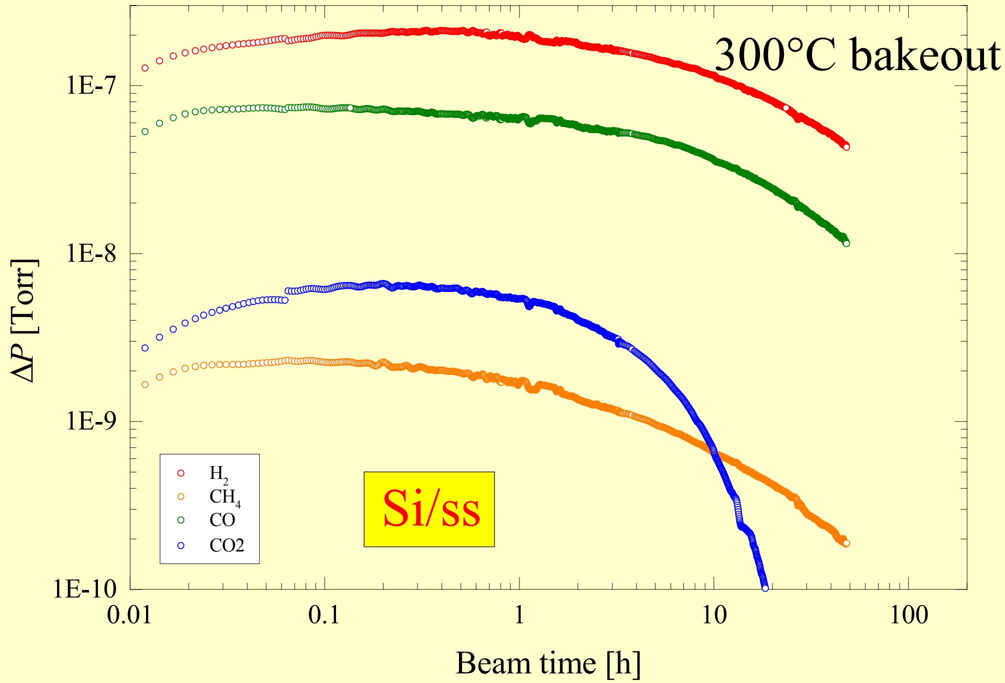


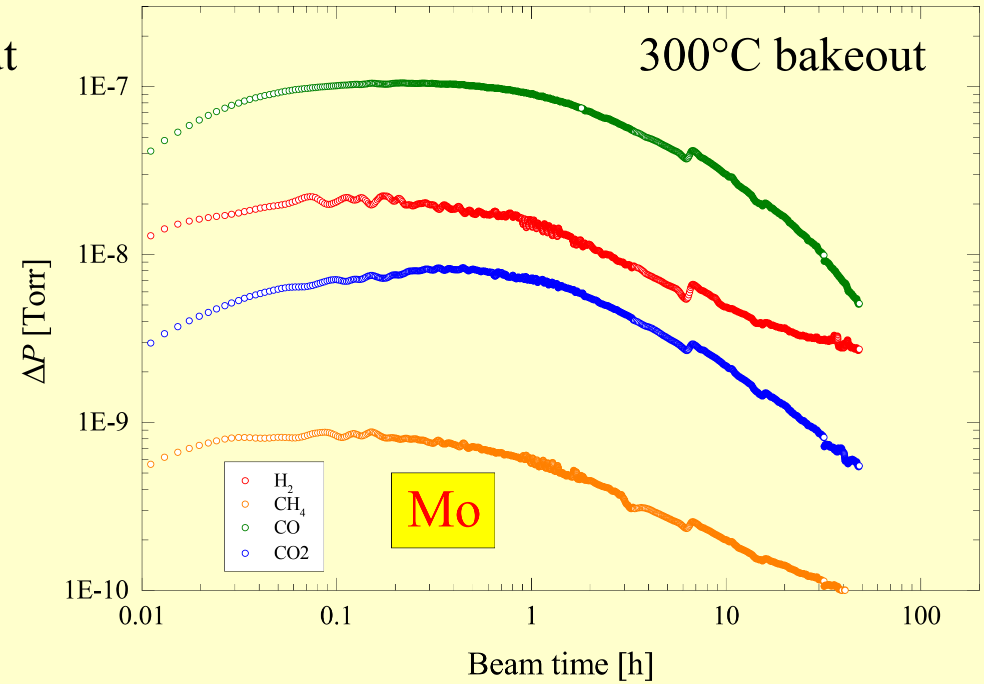


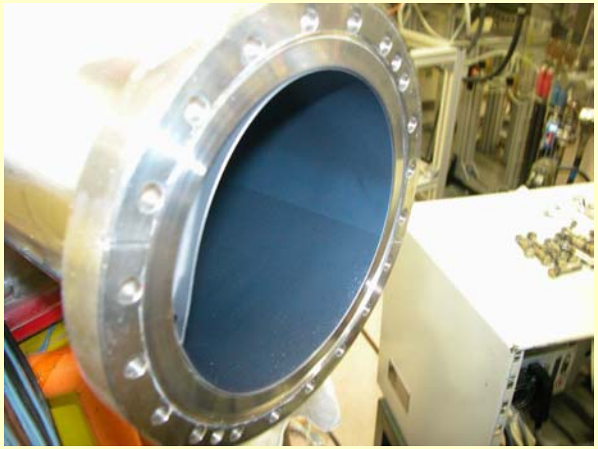


LINAC 3 beam scrubbing review (8/8)

Si/ss & Mo: partial pressures

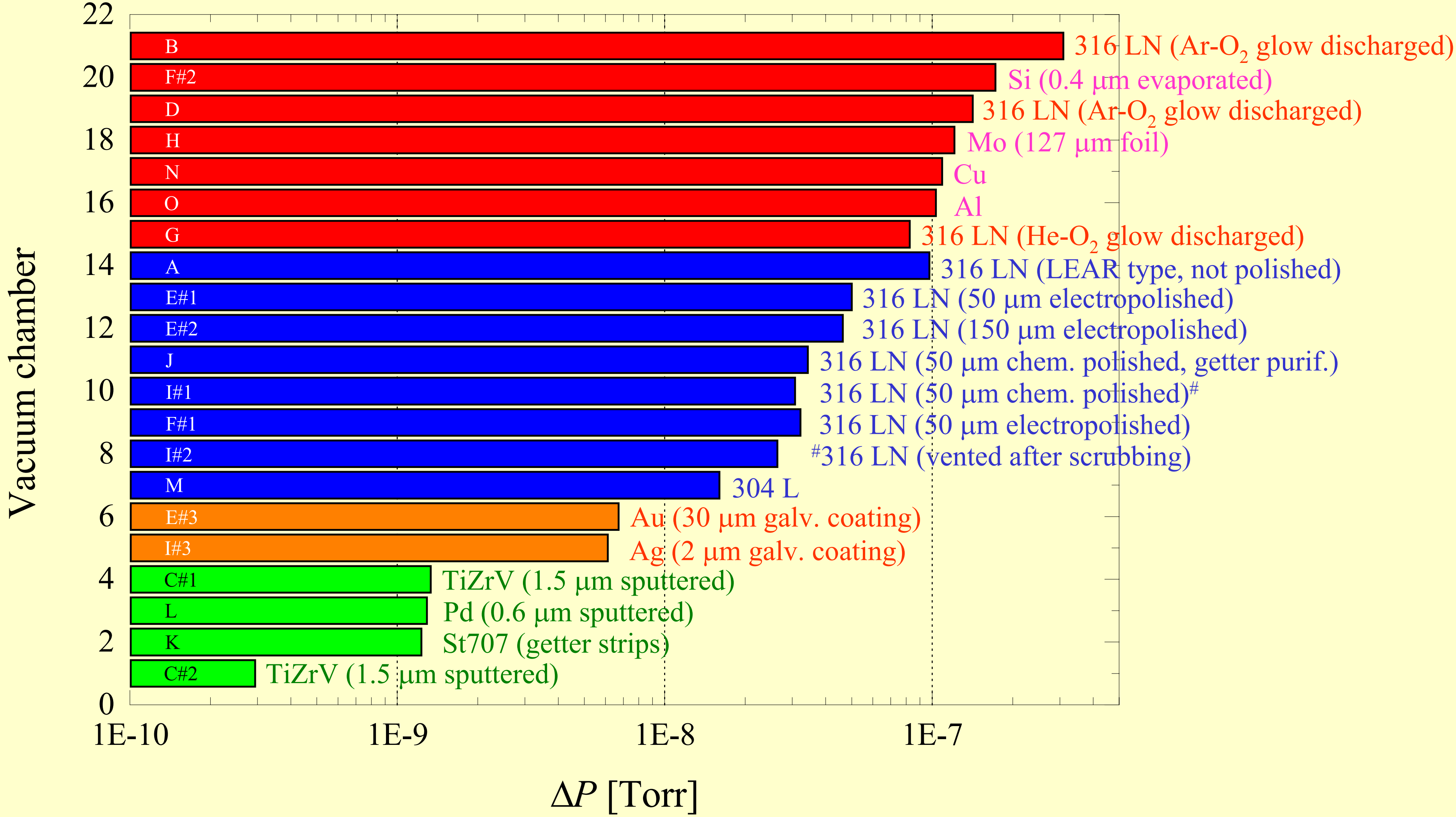






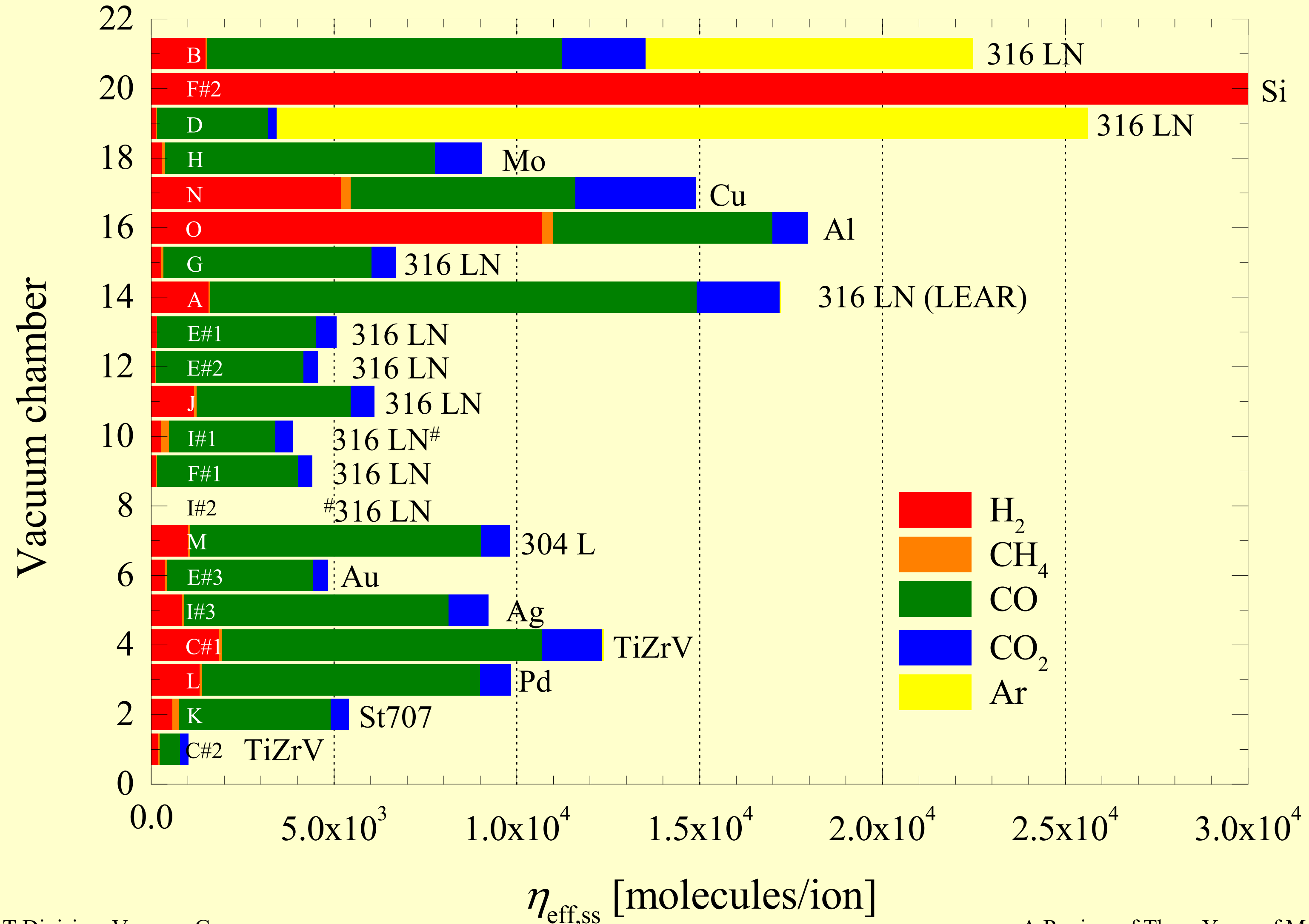
LINAC 3 review (1/3)

Pressure rise summary



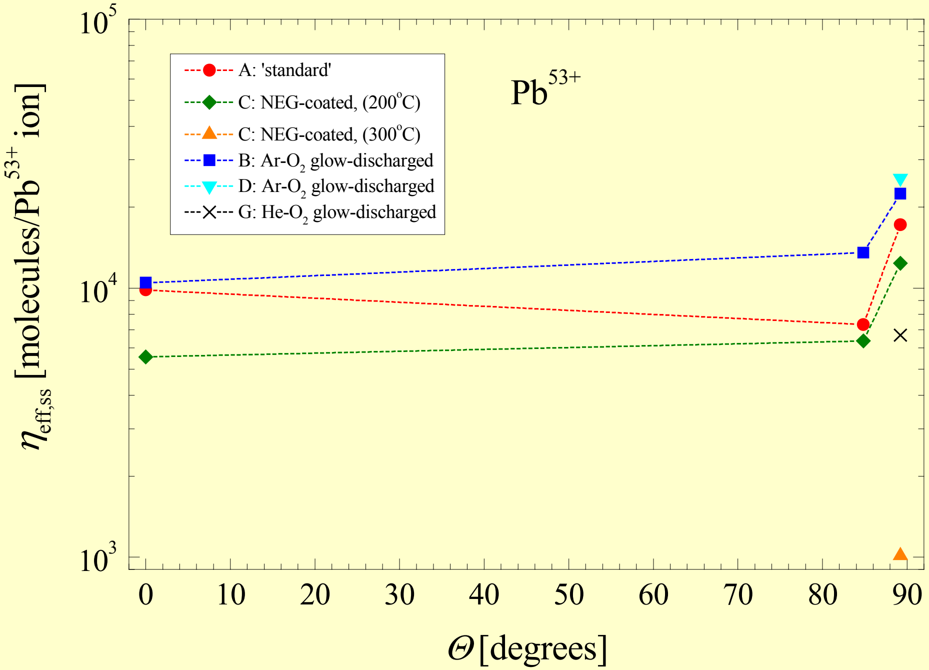
LINAC 3 review (2/3)

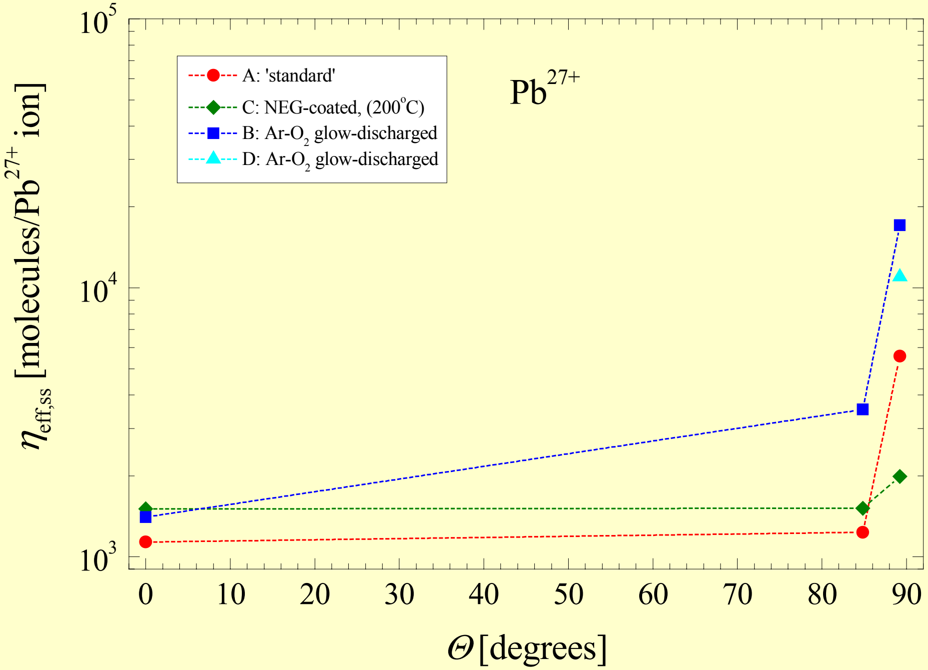
Partial pressures from single shots



LINAC 3 review (3/3)

Impact angle & charge state





- Impact angle (89.2°/perpendicular) for 316 LN stainless steel

  Factor 2 reduced η at $\theta = 0°$ → saw-toothed absorbers

- Ion charge state (53+/27+) for 316 LN stainless steel

  Factor 10 reduced η at $\theta = 0°$ → no impact for LEIR

Conclusions from LINAC 3 studies

- Origin of LEAR vacuum degradation is understood
  - Measured (2×10^4) and calculated (7×10^4) desorption yields are in reasonable agreement
  - High dynamic gas loads can be reduced by scrubbing
- Stainless steel surface treatments & coatings
  - Electropolishing or chemical etching slightly reduces η
  - Sputter coatings (NEG, Pd) and galvanic coatings strongly reduce the η
  - Improvement factors α_i (≡ reduced pressure rise compared to standard 316LN chamber):
    $\boldsymbol{\alpha_{epolish} \approx 2, \alpha_{etch} \approx 3, \alpha_{Au} \approx 15, \alpha_{Ag} \approx 16,}$
    $\boldsymbol{\alpha_{Pd} \approx 76, \alpha_{TiZrV(200°C)} \approx 72, \alpha_{TiZrV(300°C)} \approx 333.}$
- No influence found on the following parameters
  - Vacuum firing at 950°C or 1050°C, *in situ* bakeout at 300°C or 400°C
  - Thickness of the noble-metal coatings: Au (30 µm), Ag (2µm), Pd (0.6 µm)
- What is not (or only partly) studied !
  - Dependence on: **Energy**, charge state, ion type, temperature…**(SPS desorption experiment)**
  - Contribution of electrons ? Best choice of materials ? Surface or bulk effect ?
  - Is ion-induced track formation an issue for the pressure rise? (probably not)

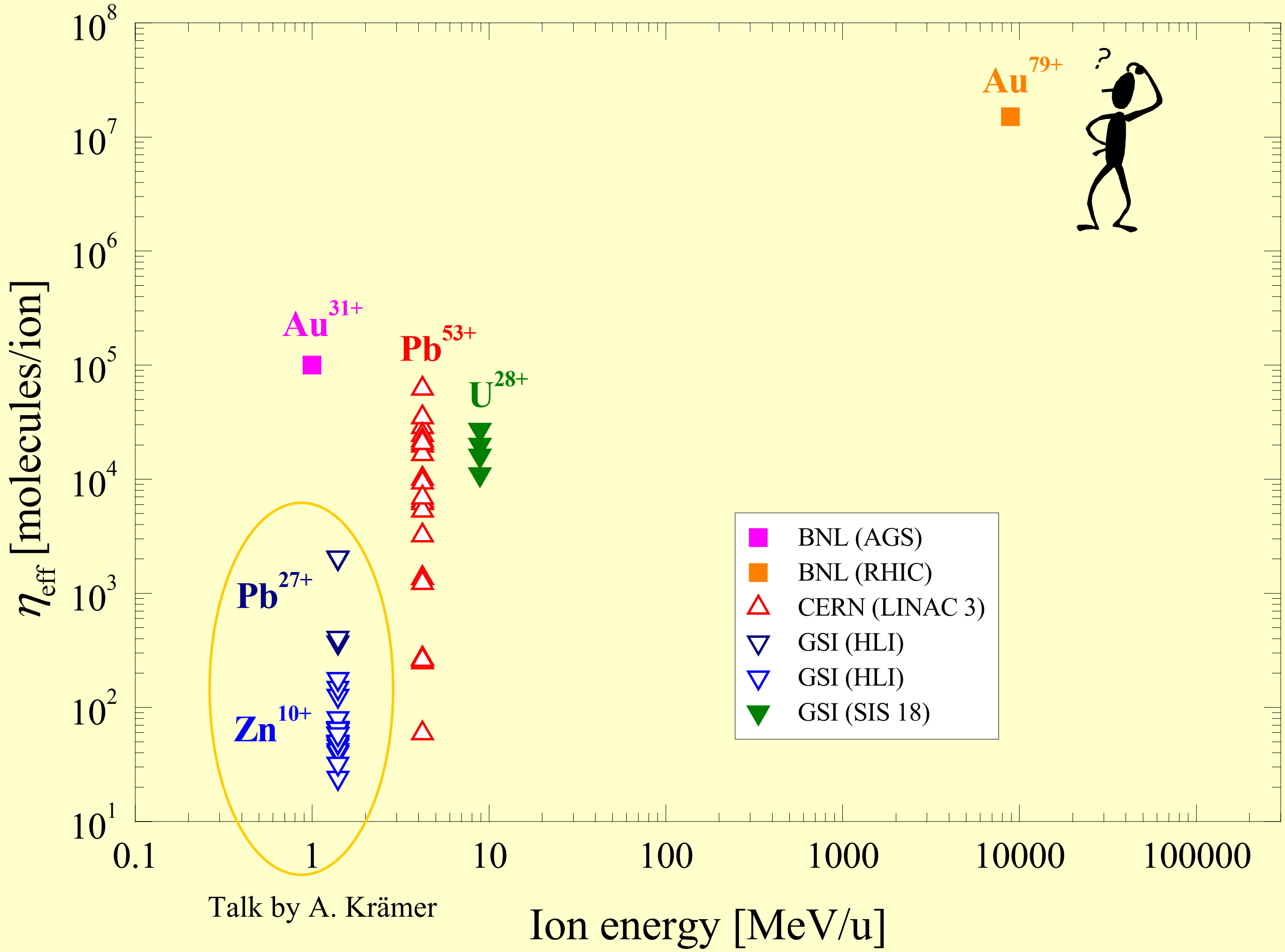
Consequences for the LEIR vacuum system

- Beam scrubbing
  - Possibility is now demonstrated for Pb ions at 4.2 MeV/u
  - Factor 10 improvement of the dynamic pressure should be feasible
  - Recover as much as possible LEAR vacuum equipment and rely on scrubbing
  - But: scrubbing is lost after venting a sector !

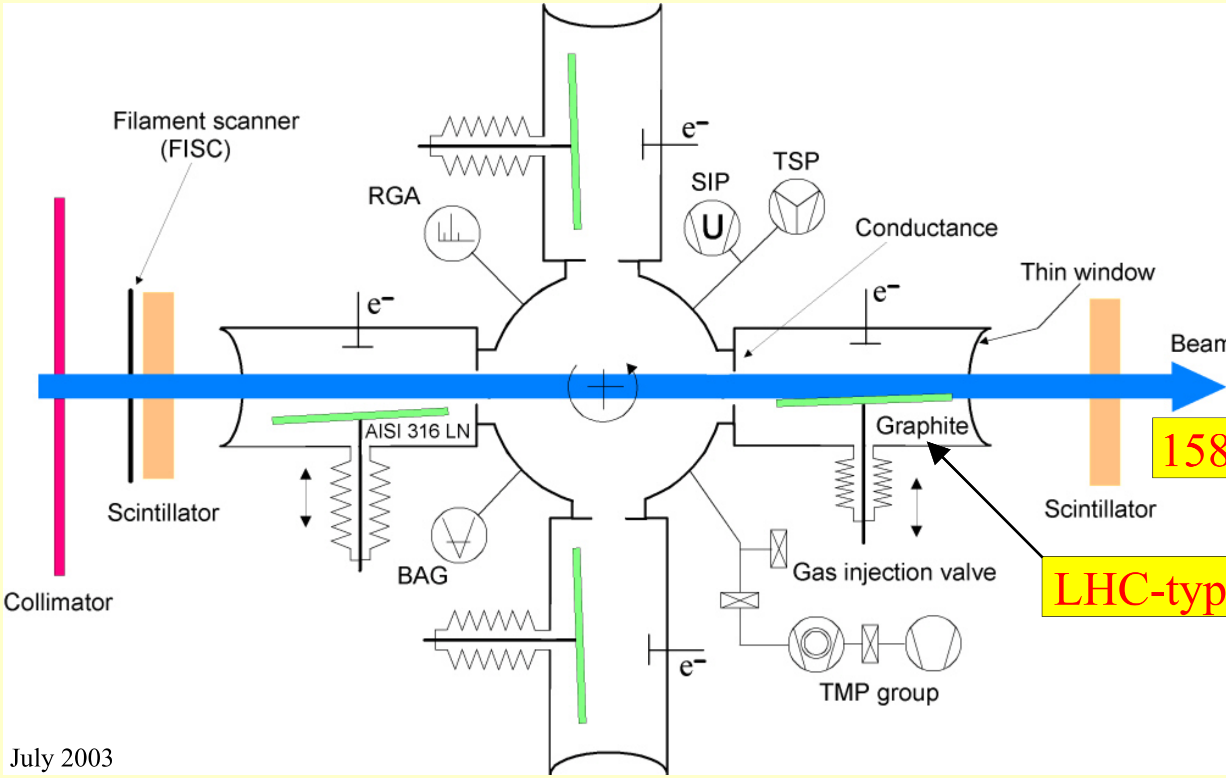
- Installation of (low cost) absorbers to reduce LEIR scrubbing time
  - Absorbers: saw-toothed 316LN sheets coated with: TiZrV, Pd, Au, Ag
  - Positioned at locations were increased ion losses are expected

- NEG coating of all LEIR vacuum chambers
  - NEG coating (wherever possible) to get:
    Very clean surfaces after *in situ* bakeout
    Low dynamic gas load under heavy ion impact

Heavy-ion induced desorption data: Overview



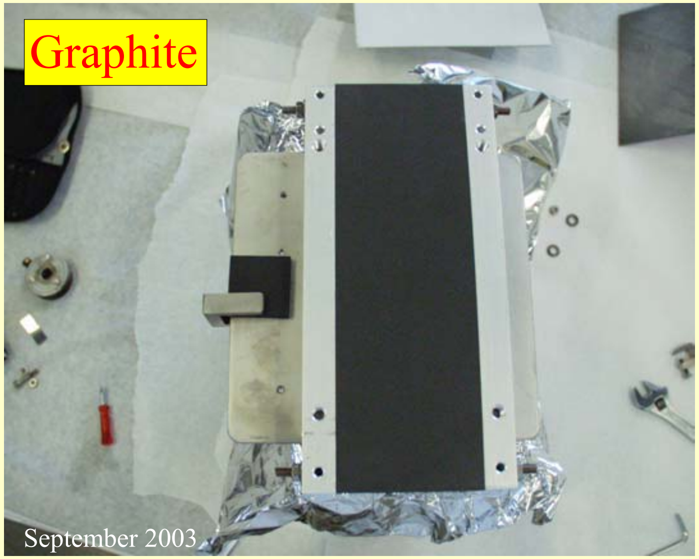
Propoposed setup for dynamic outgassing tests of LHC-type graphite collimators with In^{49+} at 158 GeV/u

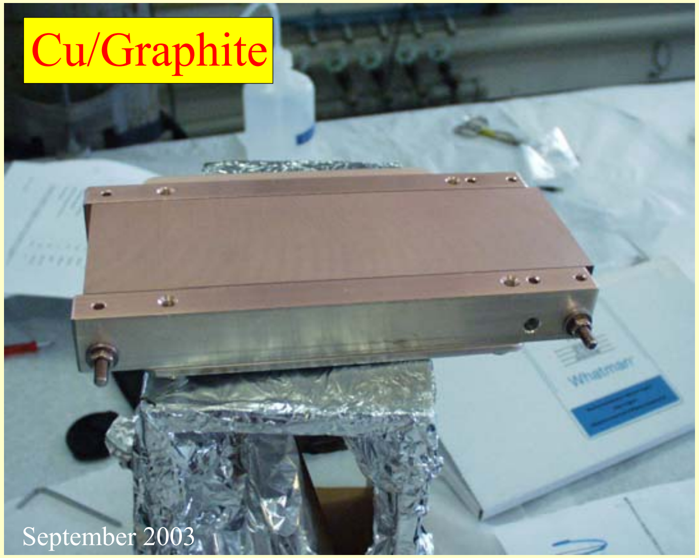


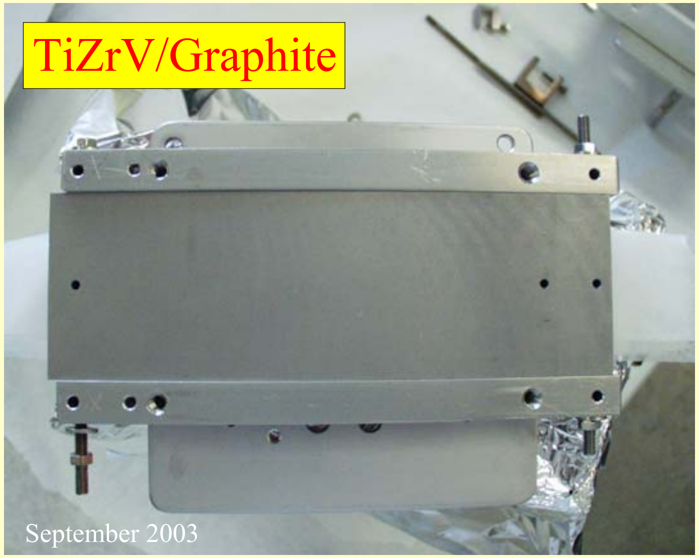
- Accelerator: SPS North Area (T4-H8)
- Beam & Energy: $^{115}In^{49+}$ at 158 GeV/u
- Intensity: 1.5×10^6 ions/spill
- Beam size: $\leq 5 \times 5$ mm^2
- Impact angle: 35 mrad

Graphite collimator coatings with TiZrV and Cu

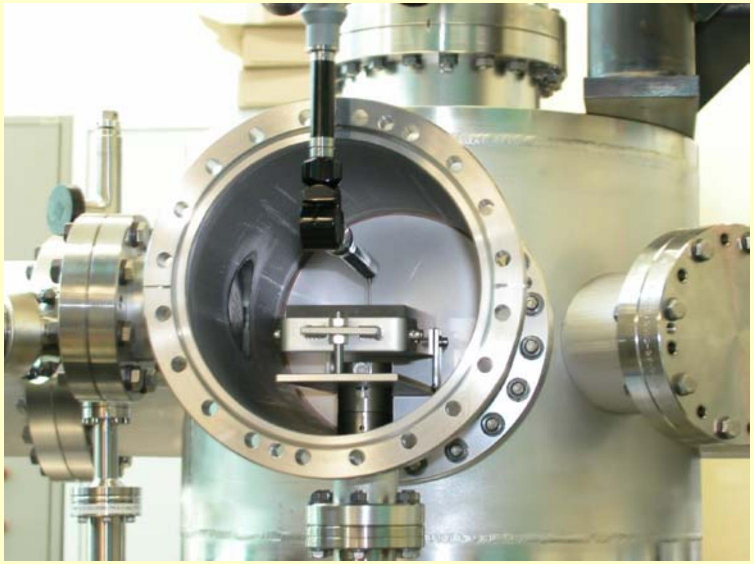
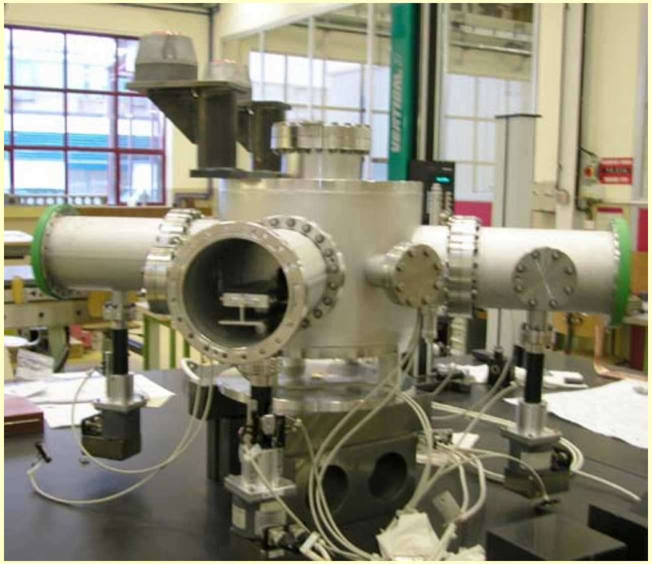
EST/SM: S. Calatroni, W. Vollenberg



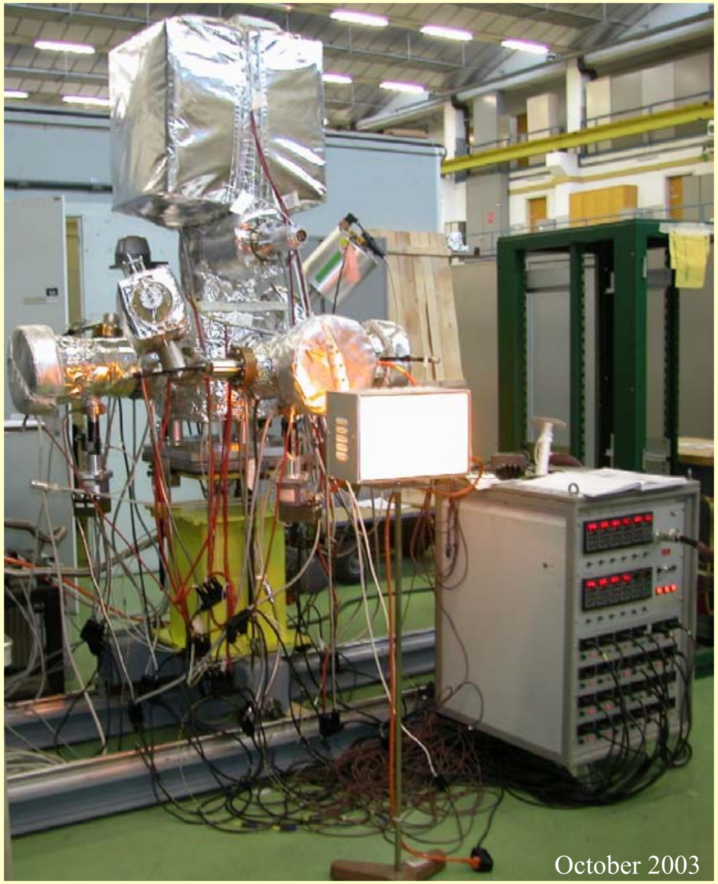




Collimator alignment in CERN main workshop

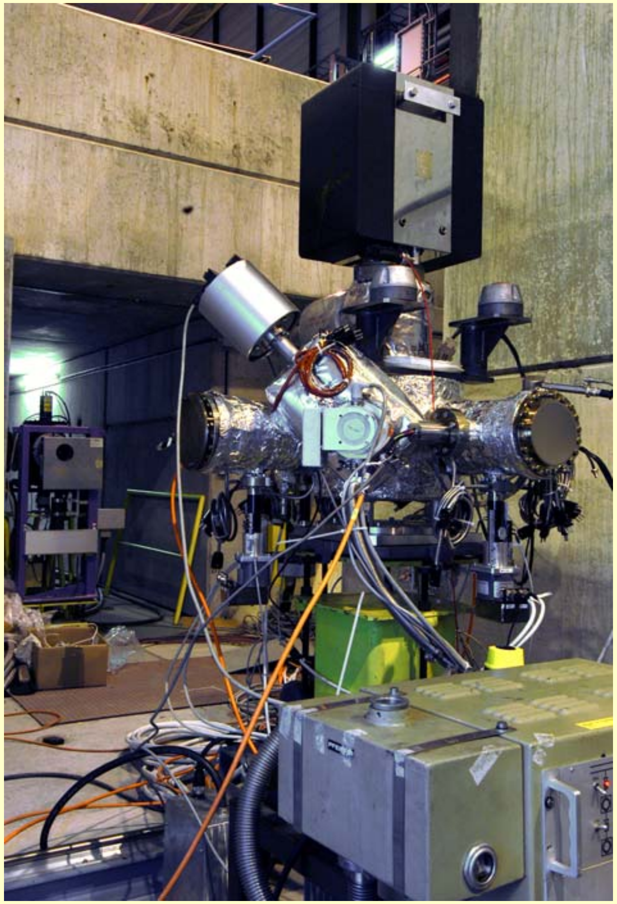
Laboratory installation + first bakeout at 300 °C

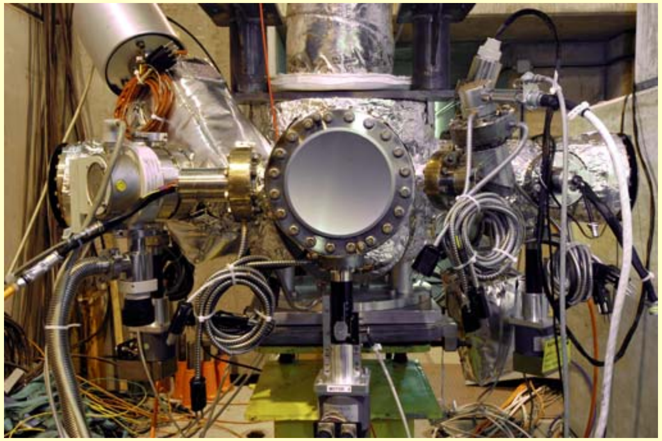


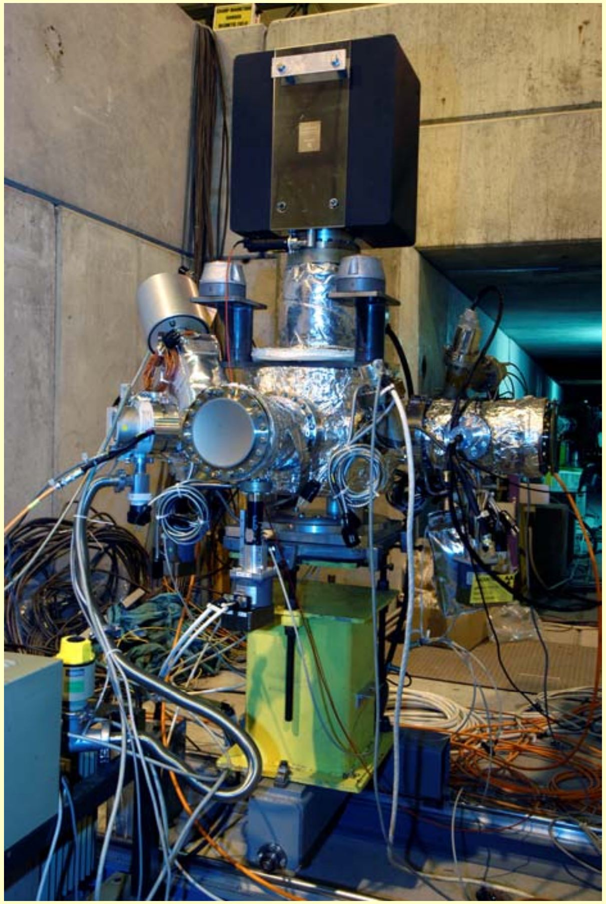
Limit pressure 72h after 1st bakeout

$P \approx 7 \times 10^{-12}$ Torr

Experimental setup installed in the SPS North Area

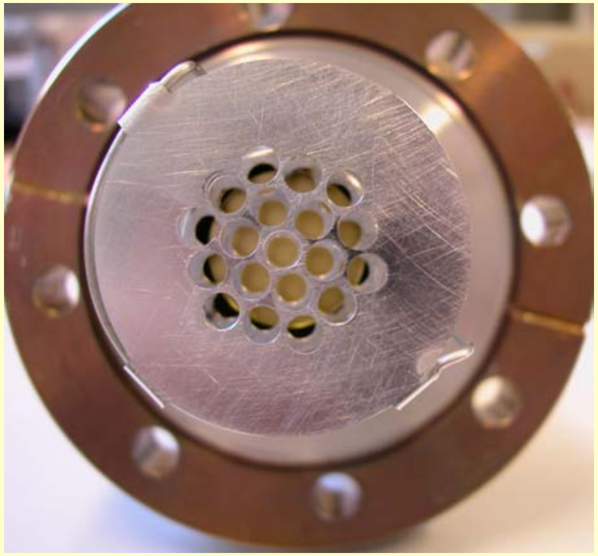






31. October 2003: Ready for beam !

Electron detectors installed in SPS desorption experiment

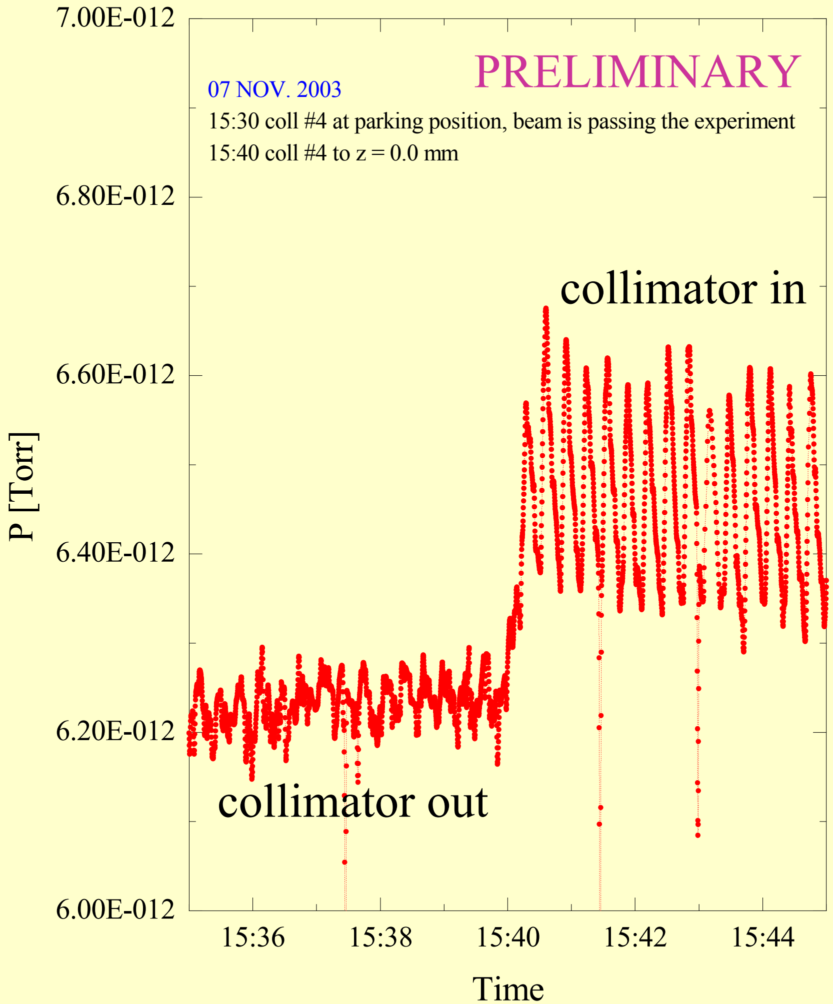


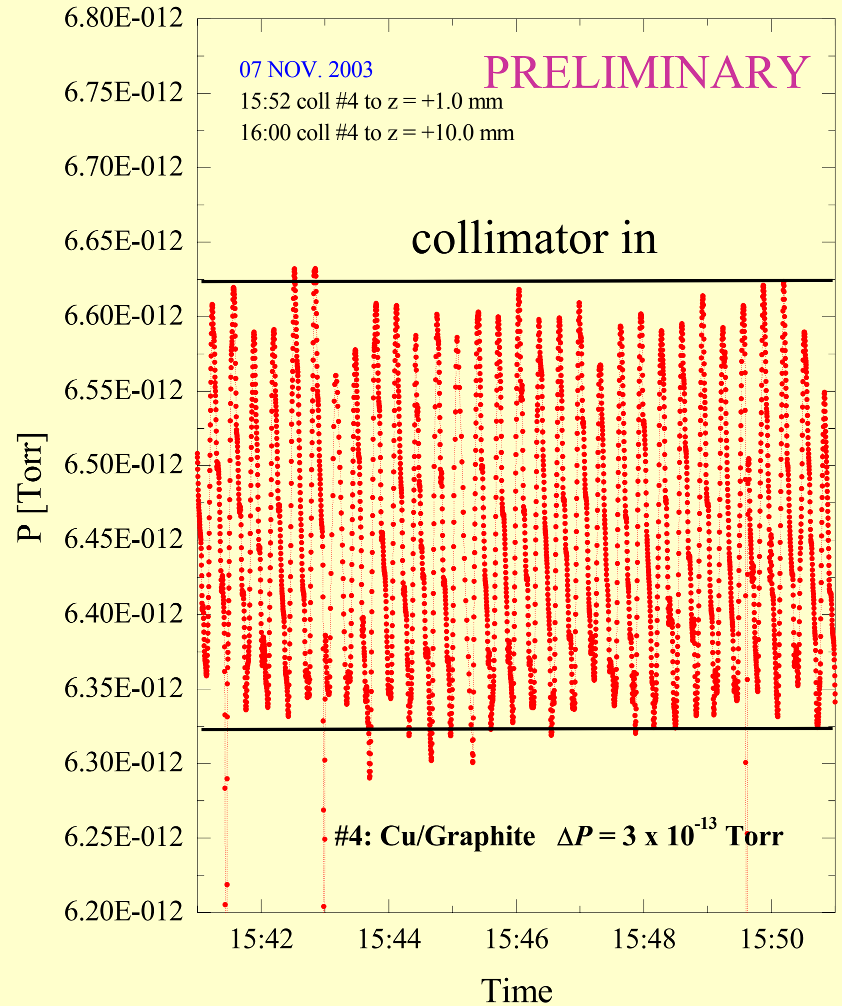
E. Page, J.-M. Laurent

Pressure rise with indium ions at 158 GeV/u

Grazing angle: 35 mrad, Intensity: 1.5 × 10^6 ions/spill

Cu (1.5 μm)/Graphite



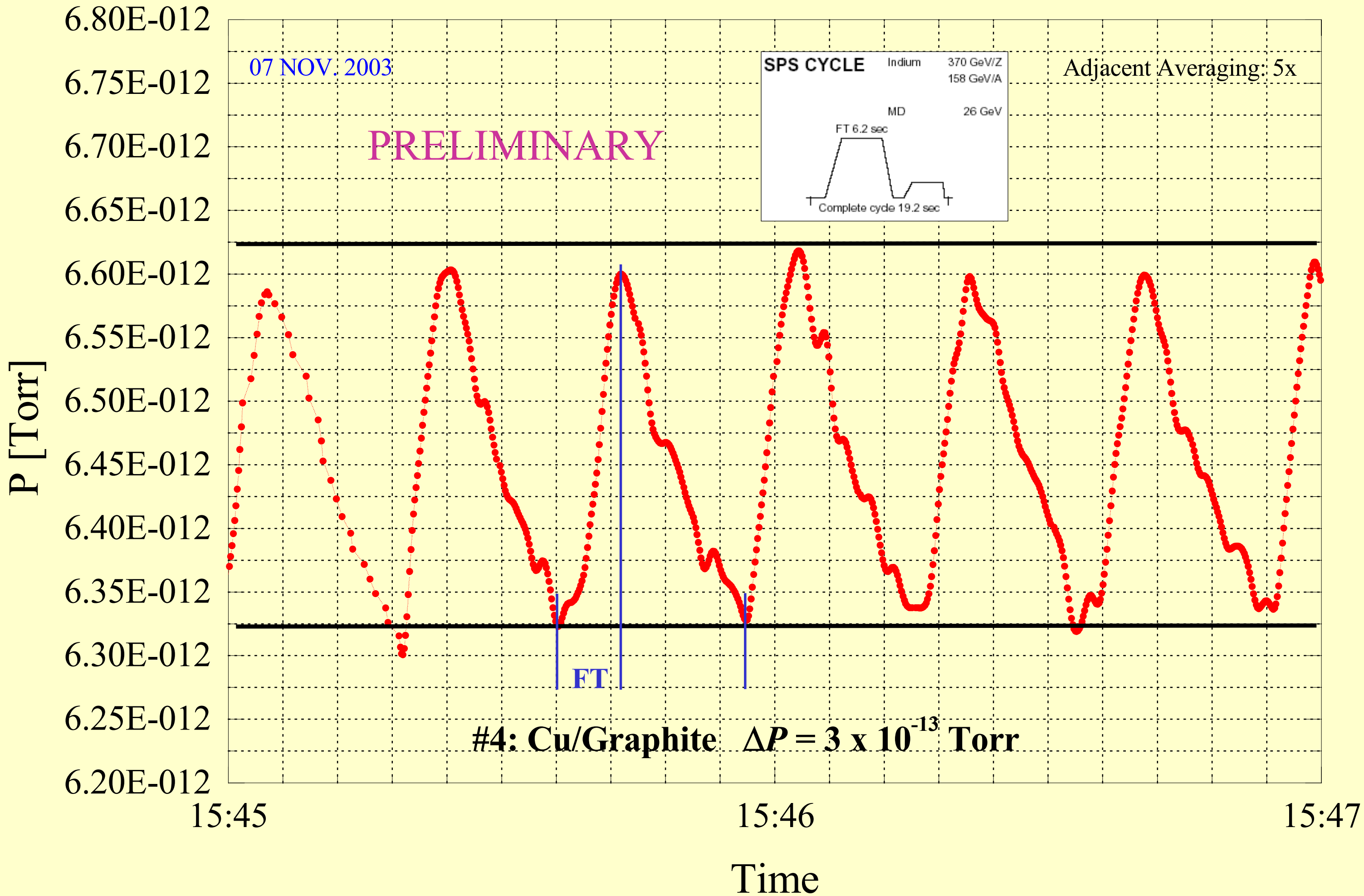


E. Mahner, E. Efthymiopoulos, J. Hansen, E. Page

Pressure rise with indium ions at 158 GeV/u

Grazing angle: 35 mrad, Intensity: 1.5 × 10^6 ions/spill

Cu (1.5 μm)/Graphite



E. Mahner, E. Efthymiopoulos, J. Hansen, E. Page

Pressure rise with indium ions at 158 GeV/u

Grazing angle: 35 mrad, Intensity: 1.5 × 10^6 ions/spill

Graphite, TiZrV (1.5 μm)/Graphite, 316 LN ss

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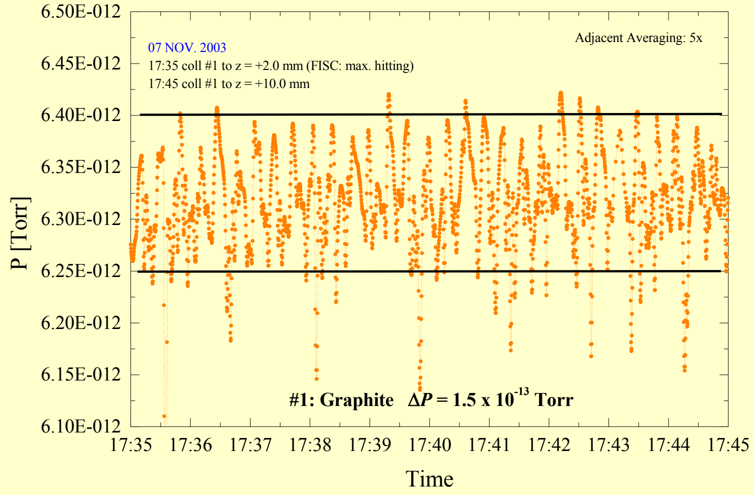
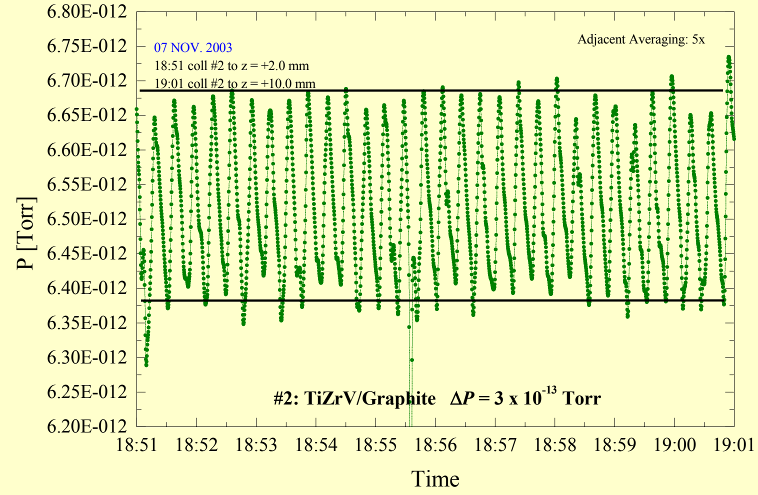
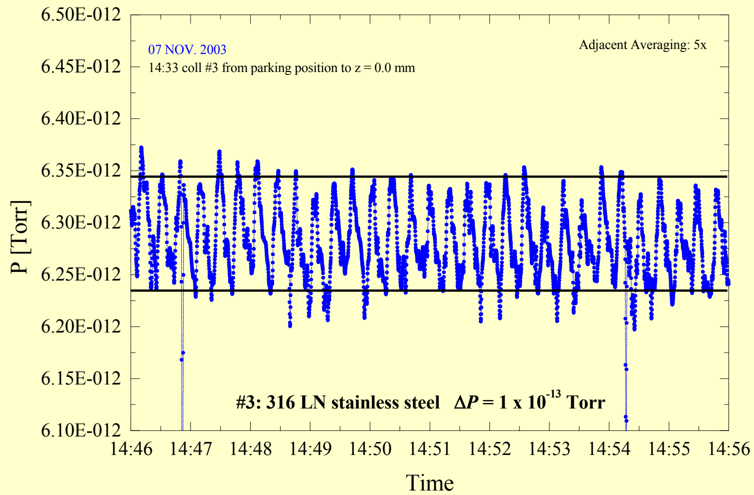






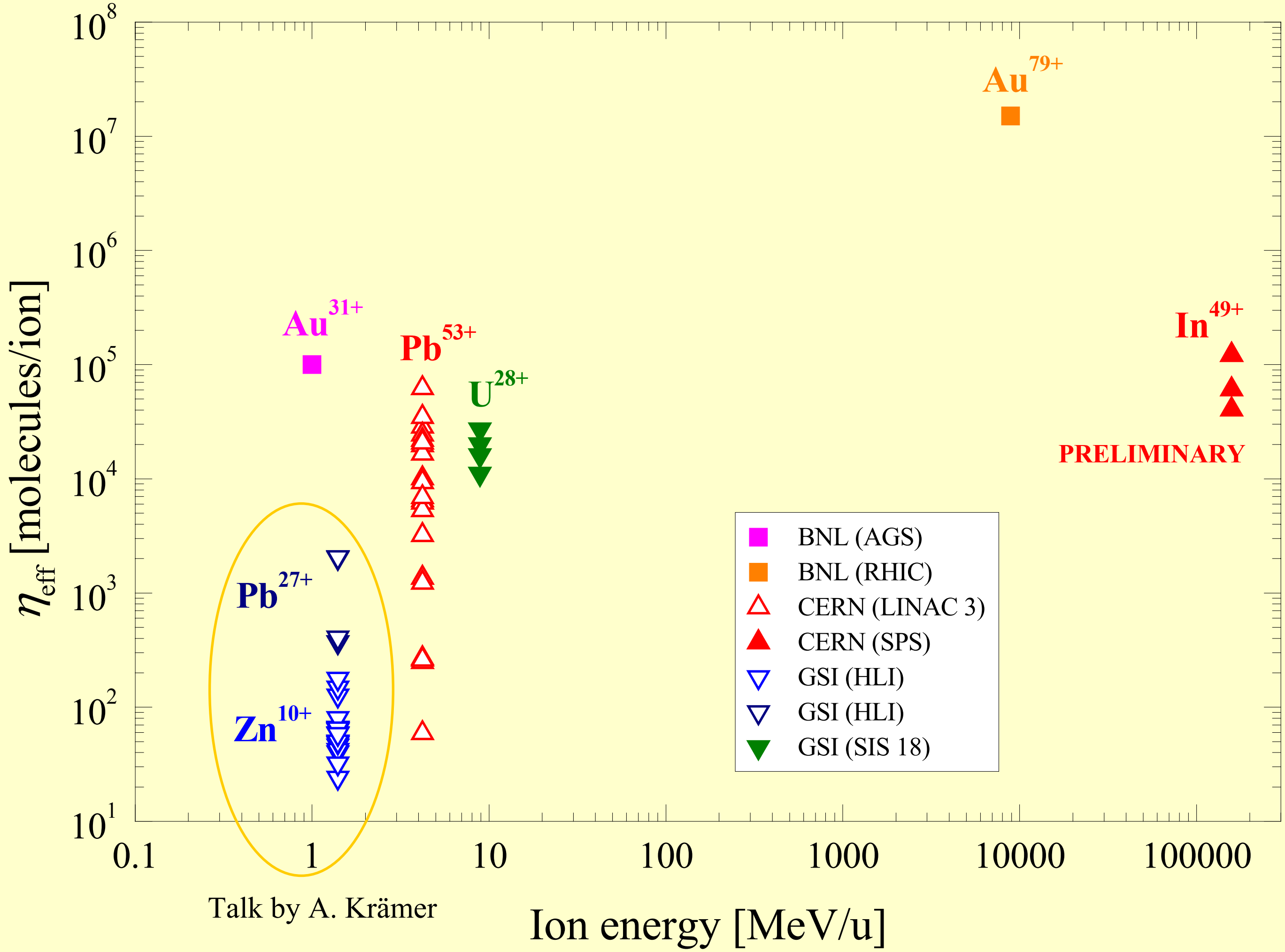
$$\eta_{eff} = \frac{\Delta P \times S}{\dot{N}_{Pb} \times k_B \times T} \approx \Delta P \times 2 * 10^{17}$$

ΔP: to correct, S: to measure, T: to calculate

PRELIMINARY desorption yields

Collimator	η_{N2} [molec./ion]
#1: Graphite	~6 × 10^4
#2: TiZrV/Graphite	~1.2 × 10^5
#3: 316 LN stainless steel	~4 × 10^4
#4: Cu/Graphite	~1.2 × 10^5

Heavy-ion induced desorption data: Overview



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  - N. Madsen, K. Magyari, E. Page, J.P. Pasquet, S. Southern, P. Strubin
- GSI & BNL collaboration
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